Biofacies as a Tool for Calibrating the Jurassic Jubaila-Arab Formational Contact from Outcrop in Riyadh area to Subsurface in Eastern Saudi Arabia

by

Abdullah G. Al-Dhubeeb

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

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In Partial Fulfillment of the
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DEANSHIP OF GRADUATE STUDIES

This thesis written by **ABDULLAH GURAID AL-DHUBEEB** under the direction of his thesis advisor and approved by his thesis committee, has been presented to and accepted by Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN GEOLOGY.**

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DEDICATION

This thesis is dedicated to my wife, um Basil, without whose patience and support I would not have been able to persevere in this task

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The work presented in this thesis would not have been possible without the help from my mentor and immediate advisor of my thesis committee Dr. G. Hughes. I would therefore like to express my deep gratitude and sincere thanks to him for this superb supervision, continuous support and professional guidance during all stages of this work. His valuable contributions, regular discussions and his encouragement significantly have helped to ensure the completion of this thesis. With his great knowledge and wise advice, Dr. Hughes also gave me many valuable and useful skills in micropalaeontological disciplines and carbonate prospective as well as life. Indeed, I feel proud to have worked with him and also associated with him as one of his students.

Many thanks to Dr. Mahbub Hussain (my committee chairman and my advisor at KFUPM) for his kind support and advice during the course of this research and during my academic courses. He helped to educate me on various aspects of carbonate and petroleum geology. I would also like to thank Dr. Osman Abdullatif (member of my thesis Committee) for his advice about my progress in my research and the industrial application of sedimentology. Many thanks go to Dr. Mustafa Hariri (Earth Sciences Department chairman) for his encouragement and his kind instructions and assistance during MSc program. I would like to thank many other staff in Earth Sciences Department at KFUPM for their continual support and for their efforts to solve administrative problems.

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The summary charts showing GR log, lithology, lithostratigraphy, reservoir zones, biofacies, palaeoenvironment and micropalaeontological analysis of study localities.

THESIS ABSTRACT

NAME: Abdullah G. Al-Dhubeeb

TITLE OF THESIS: Biofacies as a Tool for Calibrating the Jurassic Jubaila-Arab Formational Contact from Outcrop in Riyadh area to Subsurface in Eastern Saudi Arabia.

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The lithostratigraphic relationship between the Jubaila and Arab Formations is not fully understood and is often misinterpreted in the subsurface. Since the type section of the Jubaila is in the outcrop and that of the Arab is subsurface, there is no common feature to easily define the contact in subsurface. The highly productive Arab-D reservoir spans the Jubaila and Arab Formations. One reservoir layer in Ghawar field (at the top of reservoir zone 2B) is considered in previous studies to possibly equate with the Jubaila-Arab formational boundary, and it is confirmed in this study.

Semi-quantitative micropalaeontological analysis of thin sections from three localities in surface exposures of the Jubaila and lower Arab Formations in Riyadh area enables recognition of this boundary in eight wells in eight fields in the east of Saudi Arabia.

In this study, the Arab D reservoir has been divided into nine biofacies that characterize the Jubaila and Arab Formations and the nature of the Jubaila-Arab formational contact. Calibration of the wireline logs with these biofacies will assist in the recognition of this event in uncored wells, and assist in regional Arab-D reservoir layering. Such information will also contribute to improve the understanding of intra-Arab-D reservoir sequence stratigraphy, palaeoenvironmental and sedimentological variations and unexpected production behavior of the reservoir.

MASTER OF SCIECNES DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINIERALS
Dhahran, Saudi Arabia
June 2005

ملخص الرسالة

الاسم: عبدالله جريد الضبيب

عنوان الرسالة: إستخدام السحنات الحيويه المجهرية كأداة لتقويم منطقة التماس بين متكون الجبيلة ومتكون العرب من المنكشفات الصخرية في منطقة الرياض الى الطبقات التى تحت السطح في شرق المملكة العربية السعودية.

التخصص : الجيولوجيا

تاريخ نيل الدرجة: يونيو ٢٠٠٥ م

إن العلاقات الطباقية بين متكون الجبيلة و متكون العرب غير مفهومة في الطبقات التي تحت سطح الارض وغالباً ما تحدد بشكل غيرصحيح خاصة في مكمن العرب (د) في حقل الغوار. جزء من المشكلة يأتي من أن القطاع النموذجي لمتكون الجبيلة يوجد في الطبقات الظاهرة فوق سطح الأرض أما القطاع النموذجي لمتكون العرب فيوجد في الطبقات تحت السطح مما جعل تحديد التماس بينهما أمرًا صعباً.

مكمن العرب (د) من أكثر المكامن انتاجا للبترول. الدراسات السابقة وجدت أنه من الممكن معرفة التماس بين المتكونين في مكمن العرب(د) في حقل الغوارفي طبقة تسمى (ب-٢) لكن هذا يحتاج إلى دراسة تفصيلية تثبت أنه فعلا نطاق التماس.

باستخدام تحليل السحنات الحيوية المجهرية من العينات التى أخذت من ثلاث مواقع من المنكشفات الصخرية الظاهرة على السطح لهذين المتكونين في منطقة الرياض حيث التماس واضح تمت المقارنة مع السحنات الحيوية المجهرية التى وجدت تحت السطح من ثمان أبارمن ثمان حقول بترول في شرق السعودية.

في هذه الدراسة تم تقسيم كامل مكمن العرب (د) الى تسع سحنات حيوية جديدة كل منها تحتوي على مجموعة من الأحافيرالتى عاشت في بيئه ترسيبية واحدة وباستخدام هذه السحنات أمكننا ليس تحديد التماس فقط بل ساعدت في فهمنا لطبيعة التطبق في مكمن العرب (د) وبيئتة الترسيبية. وفي هذه الدراسة أيضاً تم فهم طبيعة العلاقة بين هذه السحنات وخصائص القياسات الكهربائيه للأبارحول التماس حتى نستطيع تحديد منطقة التماس من الابار التى لا تحتوي عينات صخرية.

درجة ماجستير العلوم

جامعة الملك فهد للبترول والمعادن

الظهران-المملكة العربية السعودية

يونيو٢٠٠٥

CHAPTER ONE

INTODUCTION

1.1. INTRODUCTION

Lack of understanding of the stratigraphic relationship between the Jubaila and Arab formations in both outcrop and subsurface and the presence of numerous biocomponents in the Arab-D Reservoir have necessitated a detailed investigation of the depositional cyclicity and depositional environment in both formations.

From the review of original definitions of formations (Steineke and Bramkamp, 1952a, Steineke *et al*., 1958 and Powers *et al*., 1962), the outcropping Jubaila Formation is found to be correlative with the lower portion of the Arab-D reservoir (Figure1.1). In addition, the contact between the Arab and Jubaila formations in terms of the outcrop sequence falls near the middle of the Arab-D reservoir. The top of the outcropping Jubaila Formation is equivalent to an event within the Arab D Reservoir. The Arab-D reservoir was originally defined on the presence of productive oil and is therefore not strictly a part of formal stratigraphic nomenclature.

Accurate identification of this boundary has proved to be of considerable importance for it divides the reservoir into two parts each with a decidedly different lithogenetic character and reservoir (existing reservoir zonation based on porosity logs). This study looked for biofacies fingerprints of the Jubaila and Arab formations to accurately identify the Arab D member and Upper Jubaila Formation contact regionally. By using micropalaeontological analysis of the Arab D reservoir samples from subsurface cores and outcrop sections, it has been possible to recognize nine correlative biofacies based on palaeoenvironment specific lithofacies.

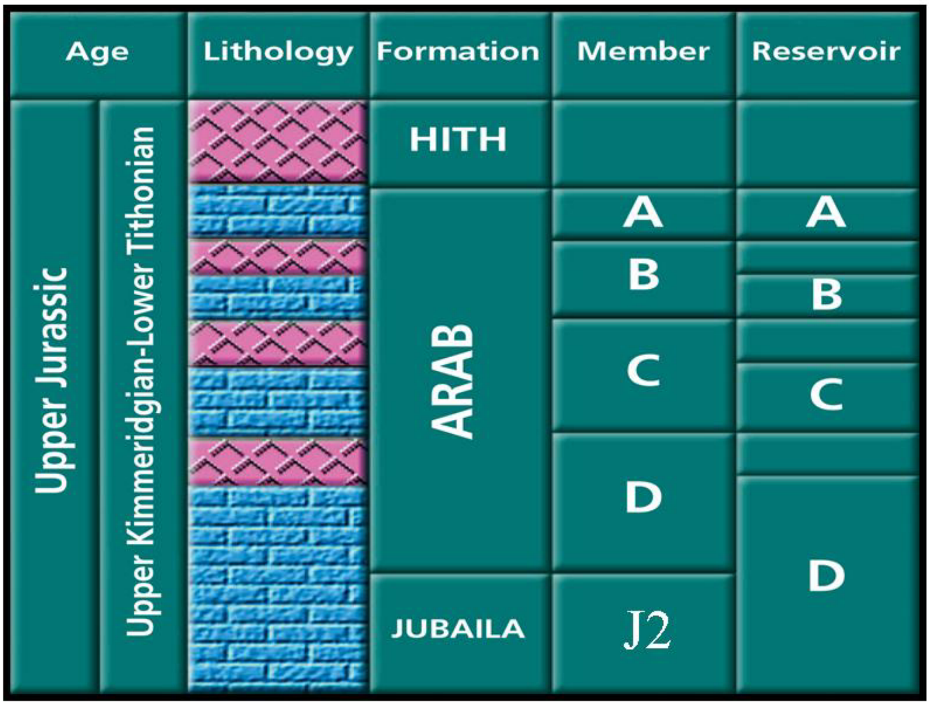

Figure 1.1. Generalized Stratigraphy of the Jubaila, Arab and Hith formations

1.2. OBJECTIVES

The main objective for studying the Upper Jurassic biofacies of the Jubaila and Arab formations is to confidently define the contact between the Jubaila and Arab formations in the subsurface. In order to accomplish this aim, the following specific objectives were defined:

1. Establish a new biofacies scheme to enable regional correlation in the subsurface.
2. Integrate nannopalaeotological data with micropalaeontological data to provide chronostratigraphic control.
3. Develop a model of the regional palaeoenvironmental setting of the Upper Jubaila Formation and Lower Arab Formation (Arab D reservoir).
4. Develop the relationship between the biofacies and reservoir zonations.

1.3. PREVIOUS WORK

The first formal description of the Jurassic carbonate succession and the naming of the component formations were made by Powers *et al.* (1966) and Powers (1968). Significant previous investigations of the lithostratigraphy and depositional environmental contributions for the Arab and Jubaila Formations in Saudi Arabia and the Middle East include Meyer and Price (1993), Alsharhan and Whittle (1995), Bouroullec and Meyer (1995), Saner and Abdulghani (1995), Yousif and Nouman (1995) and Al-Husseini (1997).

Sequence stratigraphic interpretations of the Arab-D reservoir are limited, and include Le Nindre *et al.* (1990), Azer (1995), de Matos and Hulstrand (1995), Handford *et al*. (2000) and Sharland *et al*. (2001). Biostratigraphic studies of Upper Jurassic formations and in the Middle East region are few, and limited to the significant works by de Matos (1994) and Simmons and Al-Thour (1994).

The first detailed biostratigraphic analysis of the Arab and Jubaila Formations from Saudi Arabia was by Powers (1962) and followed by Powers *et al*. (1966) and Powers (1968). A comprehensive review of macropalaeontological and micropalaeontological evidence for age determination, based mostly on ammonoids, is that of Le Nindre *et al*. (1987). The only other significant work that gives detailed micropalaeontological analysis of the Arab-D reservoir is that of Hughes (1996, 2004 and 2005).

CHAPTER TWO

GEOLOGICAL SETTING OF JUBAILA AND ARAB FORMATIONS

2.1. INTRODUCTION

The Jurassic "supercycle", as defined by Sharland *et al*. (2001), includes a succession of sedimentary formations that are characterized by their dominant carbonate lithology and, in the uppermost part, of evaporitic sediments. Lower, Middle and Upper Jurassic formations have been established, of which the Upper Jurassic contains the Hanifa, Jubaila, Arab and Hith formations. Carbonates of the upper Jubaila and lower Arab formations together contain the Arab D reservoir which represents the most prolific oil producing interval in world (Meyer *et al*., 1996). As such, it optimally combines those elements required for extremely favorable oil occurrence that include source, reservoir, trap and seal (Grunau, 1977; Bois *et al*, 1982). Oils were derived from thermally matured, Jurassic-age, organic–rich carbonate source rocks of the Tuwaiq Mountain and Hanifa Formations (Ayres *et al*., 1982; Droste, 1990) and subsequently migrated into highly porous and permeable carbonate reservoir rocks existing in large structural traps of the Arab D reservoir in Ghawar Field. Super-adjacent and highly efficient evaporate seals, overlying the Arab D, prevented further migration and ensured the containment of the oils in these large structural traps.

Previous workers have done much to clarify the role of each of these elements. The stratigraphy of the Upper Jurassic succession has been defined in great detail by many workers and while the nomenclature for this succession has evolved somewhat through time, these definitions are now generally well-recognized in the literature. Likewise, ideas regarding the structural configuration of the eastern Arabian shelf are now well-established in the literature.

Ever since studies of the Jubaila and Arab Formations were initiated in the 1950's, many workers have sought to address the question about geological features such as the origin, internal composition, architecture, and lithification of the Arab D reservoir (upper Jubaila Formation and lower Arab Formation). From these studies, formal publications developed the stratigraphic nomenclature Jubaila-Arab-Hith succession (Steineke and Bramkamp, 1952a; Steineke and Bramkamp, 1952b), and later workers have generally followed this nomenclature without significant revision (Steineke *et al.*, 1958; Powers, 1968; Wilson, 1975; Okla, 1986; Michell *et al*., 1988; Sharief *et al*., 1991; Meyer et al, 1996; Al-Husseini, 1997 and many others). Many of the initial formation descriptions and definitions were developed based on outcrop observations and were later supplemented with subsurface observations (Figure 2.1).

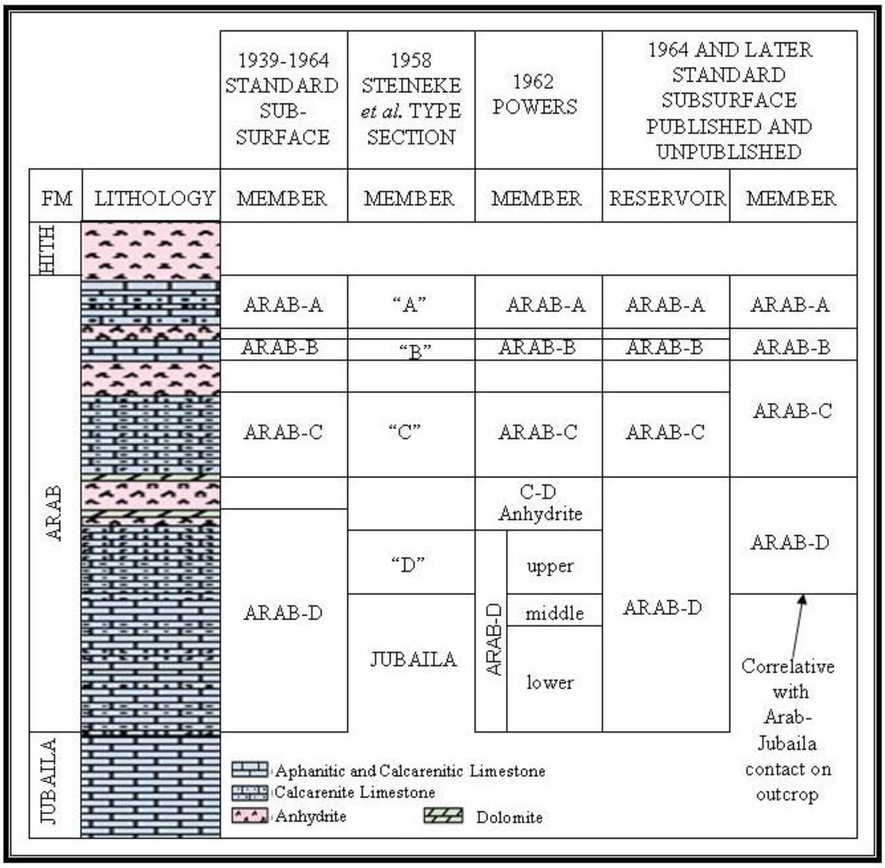

Figure 2.1. Review of historical evolution of Arab and Jubaila Formations lithostratigraphic nomenclature in the Upper Jurassic of central and eastern Saudi Arabia (as cited in Meyer *et al.* 1996 from Powers, 1968).

2. 2. LITHOSTRATIGRAPHY

2.2.1. JUBAILA FORMATION

Like the underlying Tuwaiq Mountain and Hanifa Formations, the Jubaila Formation is a carbonate that was deposited in a variety of palaeoenvironments across the Arabian shelf. Although it is mostly of mudstone and packstone texture, classically described as "aphanitic" and "calcarenitic limestone" by Powers *et al*. (1966), some highly persistent layers of "clean-washed lime sand (calcarenite)" here considered as grainstones, have been documented by Powers et al. (1966) from certain localities (Appendix A.1), particularly in the central and northern areas. Corals and stromatoporoids, few in the Riyadh-Durma area, become abundant to the north and south. Marked lateral lithological changes in the Jubaila to the south consist of a sudden shift from limestone to sandstone in the lower part of the formation and from limestone to dolomite in the upper part. Similar but less abrupt, limestone transition to sandstone also takes place to the north.

The Jubaila lithology shows relatively little change from Sha'ib al Haddar nearly to Wadi Huraymila. Over this 370 km distance, the Jubaila is well exposed in many areas, but one of the most accessible and best exposed sections is that at Wadi Nissah, was designated as a reference section (Figure 2.2) to supplement less detailed work at the type locality. The whole sequence, however, was not measured at a single locality but must be picked together from three sections. The lower 21.5 m was described (at lat 24° 14' 22" N., long 46 41' 55" E.) by E. L. Berg and R. L. Myers in 1945, the middle 30.8 m was covered (lat 24° 14' 55" N., long 46° 44' 39" E.) by R. A. Bramkamp and S. B. Henry in 1948, and the upper 68.5 m was measured (at lat 24° 13' 24"N. long 46° 48' 59"E.) by R. W. Powers and H. A. McClure in 1961. A complete description of the Jubaila sequence in Wadi Nissah is given in Appendix A.1.

Significant changes in Jubaila lithology north of the reference section first appear in the vicinity of Wadi Huraymila (lat 25° 07' N.). At this latitude, the upper part of the formation is mostly replaced by dolomite, and some clean sandstone occurs near the middle.

Little additional change takes place between Wadi Huraymila and Wadi al Atk, but beyond there is an increase in sandstone; dolomite makes up the remainder of the sequence. About 50 m of Jubaila is present a few kilometers south of Al Ghat. The lower one-third and a capping 5 to 10 m bed consist of reddish-brown dolomite; the rest of the section is mainly tan to brown, coarse-grained, calcareous cemented sandstone.

South of the reference locality, the first notable change in Jubaila rocks takes place near Shaib al Haddar. The shift can first be seen just north of Sahib where a few sandstone interbeds are present near the middle of the formation. South of the Shaib, near lat. 21 50' N., sandstone dominates the lower part of the Jubaila; the upper one-half is partly replaced by thick-bedded dolomite. Almost complete dolomite replacement of the upper limestone of the Jubaila occurs in the vicinity of Wadi ash Shutbah (lat 21° 30' N.) The lithologic pattern of dolomite above and sandstone below, that persists for at least 150 km. may be characterized by a section measured along lat 20° 37'N. The sequence here is summarized in (Figure 2.2).

The dolomite-sandstone facies can be traced without interruption beyond Wadi ad Dawasir, but near Al Hasi (lat 20° 08' N.) all sandstone is abruptly replaced by "aphanitic limestone”. From this point to where the Jubaila disappears under the Rub al Khali sand, dolomite and “aphanitic limestone” are the only rock types. Dolomite does shift stratigraphically downward along strike, however, replacing the upper Jubaila in the north and the lower part of the sequence in the south (Powers *et al*., 1966).

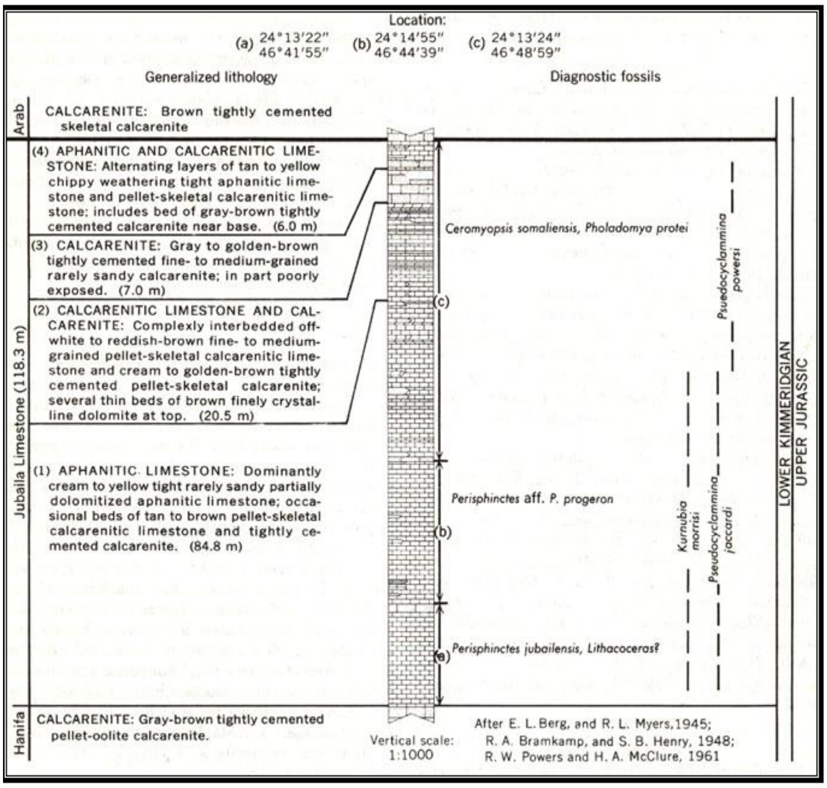

Figure 2.2. Jubaila Formation – Type Section (Powers *et al*., 1966)

2.2.2. ARAB FORMATION

Lack of good Arab formation exposure, except for the lower 15 to 25m, has prevented working out a precise lithologic sequence. The little that is known of the basic rock types indicates they are similar to those found in wells to the east. As a result, most information of the Arab has been obtained from bore holes. In fact, subsurface units, probably not differing greatly from the original outcrop sequence, have been taken as the type and reference sections.

The description of the A, B, and C Member of the Arab and the capping anhydrite of the D members in Dammam well 7, by R. A. Bramkamp and H. A. Kimball in 1955, is still the best account of the stratigraphic interval. Considerable new information has been obtained on the D member carbonate through thin-section analysis (Powers, 1962). Consequently, the better understood sequence in Abqaiq well 71 (lat 26° 18' 28"N., long 49° 45' 45"E.) between a depth of 2,223 and 2,260 m was designated as a reference section for this unit (Figure 2.3).

Thicknesses of individual members change little from the coastal area toward the outcrop. Each anhydrite bed does, however, thicken considerably, a change compensated for by thinning of the underlying carbonate unit. There is little doubt that, to the west, carbonate beds are progressively replaced from the top down by facies change to anhydrite. In fact, regional lithofacies studies show that maximum evaporite development, presumably mainly or entirely anhydrite, occurred along a north-south line near the longitude of Riyadh, where the amount of carbonate rocks remaining in the solution-collapse zone is small and the interval was apparently mostly soluble anhydrite.

Steineke, Bramkamp, and Sander (1958), in their concise description of Arab outcrop characteristics, point out that only a basal unit of carbonate rocks 15-25 m thick remains. Even within this, along nearly the entire length of its outcrop, a persistent brecciated zone suggests that at least one thin, highly persistent evaporate layer was included above the basal carbonate unit. Little is known of the true rock sequence as good exposures are few and fragmentary because extensive solution-collapse phenomena have almost entirely eliminated outcrops of the anhydrite (Figure 2.4). Dropped masses of the younger Cretaceous rocks occupy the eastern part of the solution-collapse zone, and dolomite and other carbonate rocks representing thin carbonate members, possibly equivalent to the “A”, “B” or “C members” of the Arab of the Eastern Province, show at the surface in the western part.

The basal unit of carbonate rocks referred to by Steineke, Bramkamp, and Sander (1958) has been measured and studied at several localities between Al Hasi (lat 20° 08’N.) and Wadi al Atk (near 25° 30’ N.). Over this entire distance there is little major variation in lithologic content except for increased dolomitization in the north and south. The basal Arab Carbonate unit described above is considered to be equivalent to the lower part of the type D Member at Dammam well and it may well represent the total D Member, not replaced by anhydrite, in wells as far west as Khurais and Ma’qala.

Only at the southern end of the solution-collapse zone have beds been found in place above the basal unit. Between Shaib al Haddar and Al Hasi, outcrops of anhydrite rest directly on the laterally persistent calcarenite that makes the top of the basal sequence. These overlying beds have an average thickness of about 14 m and are mainly white anhydrite and gypsum with thin interbeds and caps of brown dolomite. Little is known of the Arab sequence in outcrops above this stratigraphic level (Powers *et al*., 1966).

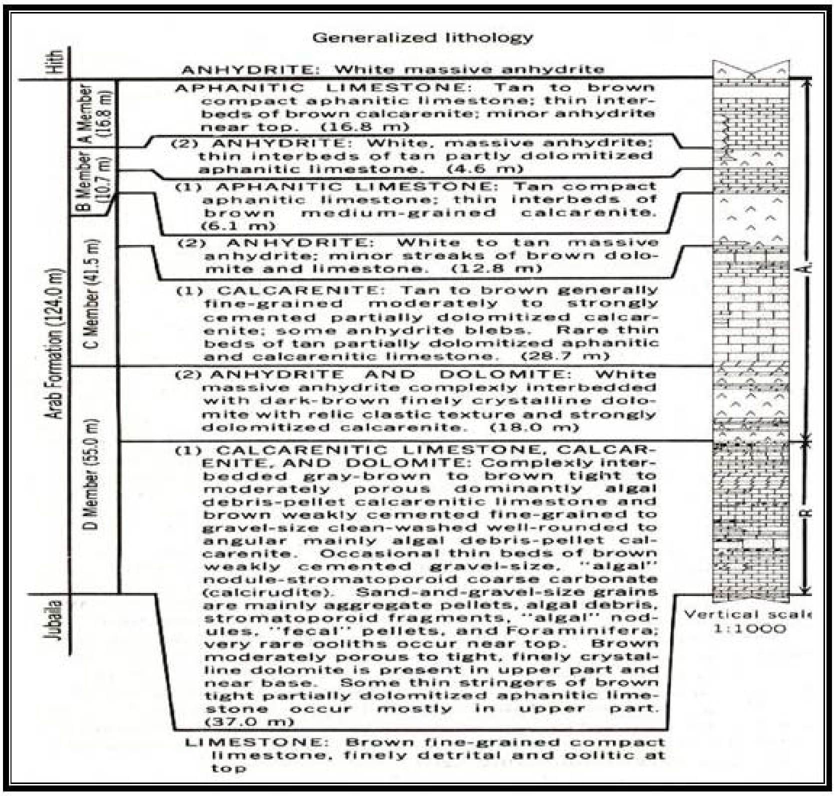

Figure 2.3. Arab Formation type and reference section (Powers *et al*., 1966)

2.2.3. CHARACTERISTICS OF THE JUBAILA-ARAB CONTACT IN SURFACE EXPOSURES

The upper limit of the Jubaila is a sharp lithologic and topographic boundary (Figure 2.5). A pattern which maintains itself for more than 700 km starts at the base with a thin calcarenite (unit 3, Appendix A.1) overlain by 6 to 10 m of gray, tight, chippy-weathering “aphanitic limestone” locally with interbeds of calcarenite and calcarenitic limestone (unit 4, Appendix A.1). The top of this lime-mud interval marks the conformable contact of Jubaila and Arab Formations. Above is a light-colored unit of softer rocks, commonly complexly interbedded aphanitic limestone and calcarenite. This is, in turn, overlain by breccia presumably representing the residuum after solution of a thin anhydrite bed.

The uppermost Jubaila unit of “aphanitic limestone” commonly weathers to a resistant dip slope. At the foot of this gentle slope is an irregular, highly discontinuous band of softer gray carbonates of the Arab Formation. Solution alteration of the Jabel Tuwaiq upland surface locally obscures the upper contact, a phenomenon that does serve a useful purpose, however, as it permits easy photodistinction between the contored beds of the Arab Formation and the flat, undisturbed Jubaila surface.

Much of the lithologic pattern so characteristic of beds bracketing the Jubaila-Arab contact at outcrop can be recognized in the subsurface sequence. This is particularly true of the aphanitic bed at the top of the Jubaila, which is equally obvious in the surface and subsurface. This unit corresponds to the middle Arab D member (Powers, 1962) that subdivides the prolific Arab D reservoir in Ghawar and other coastal oil fields. The widespread distribution of this muddy limestone and the more fragmental carbonate units flanking it suggests changes that must have influenced sedimentation over much of the basin so far studied (Powers *et al*., 1966).

2.2.4. CHARACTERISTICS OF JUBAILA AND ARAB FORMATIONS IN THE SUBSURFACE (ARAB D RESERVOIR)

Previous workers (Mitchell *et al*., 1988) have developed a classification scheme to organize Arab D rocks into genetically meaningful packages. This classification divides Arab D rocks into six depositional lithofacies, which include one anhydrite and five carbonate lithofacies. The carbonate lithofacies are distinguished on the basis of their typical depositional components, and include: (1) skeletal-oolitic limestone and dolomites. (2) *Cladocoropsis* limestones and dolomites. (3) stromatoporoid-red algal-coral limestones. (4) bivalve-coated grain-intraclast limestones, and (5) micritic limestones and dolomites. Since dolomitization frequently destroys all evidence of original depositional lithofacies, the diagenetic lithofacies dolomite was added (Mitchell, 1988). While some later workers have sought to revise this classification some what (Meyer and Price, 1993; Meyer *et al*., 1996; Handford *et al.,* 2002), these later modifications were not widely accepted and have since fallen out of use.

Figure 2.4. Jubaila-Arab boundary in Okla Section in Wadi Nissah.

Figure 2.5. Extensive solution-collapse of Arab D or C member anhydrite in Riyadh City.

2.3. AGE

2.3.1. JUBAILA FORMATION

The age of the Jubaila is mostly based on ammonite evidence provided by the exposures, as ammonites are rarely encountered in cores. Foraminiferal and calcareous nannofossil evidence is of supportive value only. Arkell (1952) places the Jubaila Limestone in the lower Kimmeridgian on the basis of the perisphinetid ammonites *Perisphinctes jubailensis* Arkell, *Perisphinctes* aff. *P. progeron* von Ammon and the nautiloids *Paracenoceras wepferi* and *P.*gr.*moreausum* (Tintant, 1987).

Kurnubia morrisi Redmond and *Pseudocyclammina jaccardi* (Schrodt) occur at the same level as the ammonites. The presence of *Pseudocyclammina jaccardi*, now termed *Alveosepta jacardi* fits in well with Arkell's determination since this foraminifer is known to range from the upper Oxfordian into the lower Kimmeridgian. It should be noted, however, that this species is not easily distinguished from the related species *Alveosepta powersi*, except by critically located sections that provide detail on the septal character (Whittaker, 1998).

Pseudocyclammina powersi Redmond occurs in the upper part of the formation, above the range of *Pseudocyclammina jaccardi*. The beds carrying *Pseudocyclammina powersi* likewise fall within the lower Kimmeridgian, if Hudson and Chatton (1959) are correct in equating the stratigraphically higher group g Ashab limestone with the *Cidaris glandarius* beds of the Lebanon and Kurnub areas (Powers *et al*., 1966).

Age diagnostic foraminifera encountered in surface and subsurface studies by Saudi Aramco include *Alveosepta jacardi, Kurnubia palastiniensis, Trocholina* *palastiniensis, Pfenderina salernitana, Mangashtia viennoti*, in the absence of *Redmondoides* species, *Pfenderina trochoidea* and *Riyadhella regularis.*

Based on regional evidence and correlation, Sharland *et a*l. (2001) have proposed a maximum flooding surface within the lower part of the Jubaila Formation (MFS J70, 152.75Ma, late Kimmeridgian).

Calcareous nannofossil evidence by Dr. Varol, O. (2001) indicates that a Kimmeridgian age may be deduced from the presence of the ascidian spicules *Velasquezia spp., Ascidites gigas, Paleodidemnum spp. and Ascidites elongatus.*

2.3.2. ARAB FORMATION

The age of the Arab Formation is poorly defined, and based on rather inconclusive macrofossil and microfossil evidence. Certain biofacies have been found to characterize particular levels within the Arab-D carbonates in the subsurface, and thereby provide stratigraphic, although diachronous, evidence for the Formation, but do not provide age confirmation.

The rather limited fauna so far recorded from surface exposures of the Arab Formation has not proved diagnostic. Except for *Diceras,* identifiable forms range down into the Jubaila below. Consequently, the subsurface sequence provides the only means of dating Arab rocks. *Kurnubia* spp. *Nautiloculina* spp., *Clypeina jurassica* Farre, C. cf. *hanabatensis* Yabe and Toyama, *Cylindroporella arabica* Elliott, *Thaumatoporella parvovesciculifera* Elliott and *Salpingoporella sp*. range throughout the Arab-D Member (Powers, 1962). Although some elements of this assemblage extend on into the A

Member, it is only the beds of the D Member that have been reliably dated (Powers *et al*., 1966).

Based on regional evidence and correlation, Sharland *et al.* (2001) have proposed a maximum flooding surface near the base of the carbonates of the Arab-C member of the Arab Formation (MFS J80, 151.75Ma, late Kimmeridgian), near the base of the carbonates of the Arab-B member of the Arab Formation (MFS J90, 151.25Ma, late Kimmeridgian), possibly near the base of the carbonates of the Arab-A member of the Arab Formation (MFS J100, 150.75Ma, late Kimmeridgian) and within the Hith Formation (MFS J110, 147Ma, late Tithonian).

2.4. PALEOGRAPHIC SETTING

During the Upper Jurassic (between about 131 and 152 million years ago (Haq *et al.,*1988), eastern Arabia, western Iran and Iraq formed part of the southern margin of the Tethys Ocean, a major seaway which separated the African and Eurasian crustal plates prior to the opening of the present Atlantic Ocean (Figure 2.6). At this time a vast, shallow carbonate shelf extended from central Saudi Arabia, near the present site of Riyadh, as far east as the present Zagros Mountains of Iran and as far north as central Iraq. The Arab and Hith formations were deposited on this shallow marine shelf as uppermost units of a thick succession of Jurassic carbonate sediments.

Deposition during the Jubaila, Arab and Hith time continued to reflect patterns established previously, during older parts of the section. Overall, sedimentation occurred on a broad, relatively stable shallow shelf or platform that was bounded (during Jubaila and Arab Formations time) by a series of intra-shelf basins (Figure 2.7). To the north lay the Gotnia Basin, while the Rub'al Khali Basin lay to the south; these basins continued to be sites of relatively deeper water sediments, although they show local evidence of infill by actively prograding shelf edge carbonates (Ziegler, 2001). To the west lay the Arabian shield, while the Qatar-Surmeh High was located to the east. Overall, the plaeoclimate was probably hot and arid, much like today's climate on the Arabian Peninsula. Handford *et al*., (2002). (Figure 2.8) also show the general distribution of evaporates within the Hith Formation, that formed in response to a restriction of the shelf (and especially of the intra-shelf basins) from open marine circulation; evaporates are typically thickest (and most halite-prone) in the intrashelf basins (Cantrell, 2004).

The palaeoenvironmental significance of the Middle East benthonic foraminifera is the least well known, although individual species have received attention in the Mediterranean region (Pelisse and Peybernes, 1983). The palaeoenvironment of various complex-walled agglutinated species is briefly considered by Banner and Highton (1990), *Alveosepta* species by Banner and Whittaker (1991) and *Trocholina* species by Manicelli and Coccia (1999). More detailed information on Saudi Arabian foraminiferal assemblages has been presented by Hughes (1996, 1998, 2000, 2001, 2002a, b and c, 2004a, c and d; Meyer *et al*., 2000) based on detailed studies of the vertical successive appearance of the various species, in samples from cored oil well and exposed sections, and their relationship to the host carbonate fabrics.

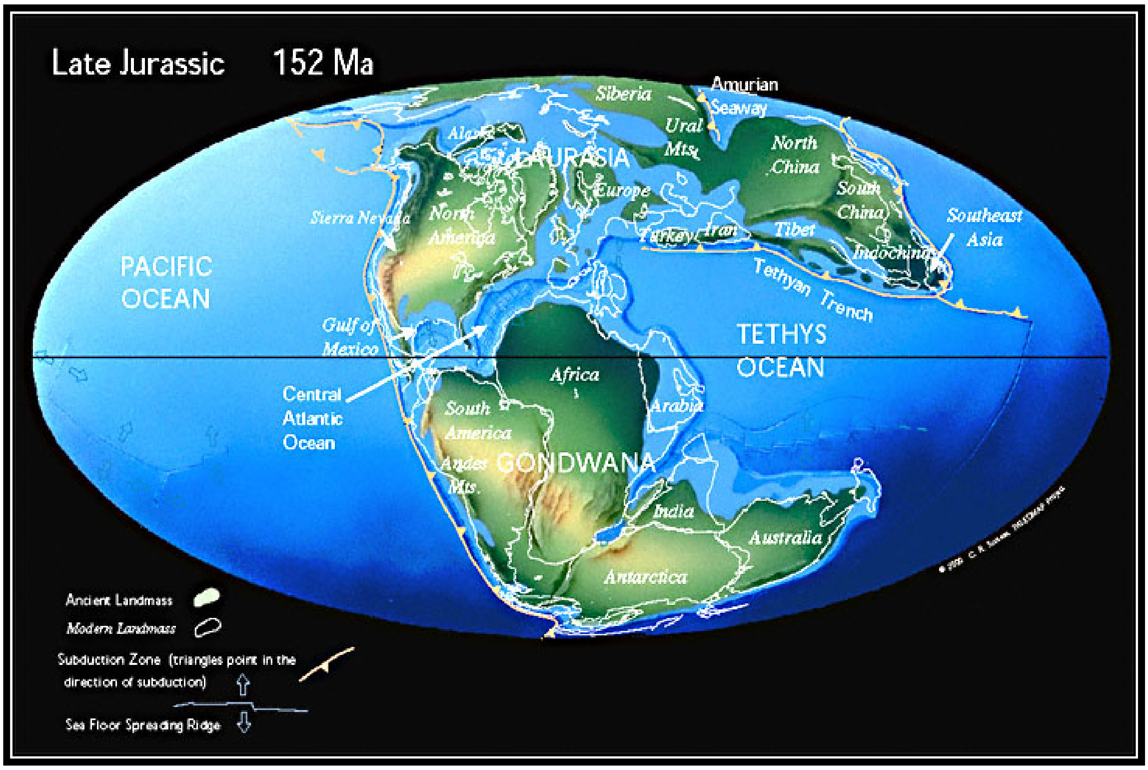

Figure 2.6. Late Jurassic paleogeography, showing the location of the major continents (from scotes, 2001).

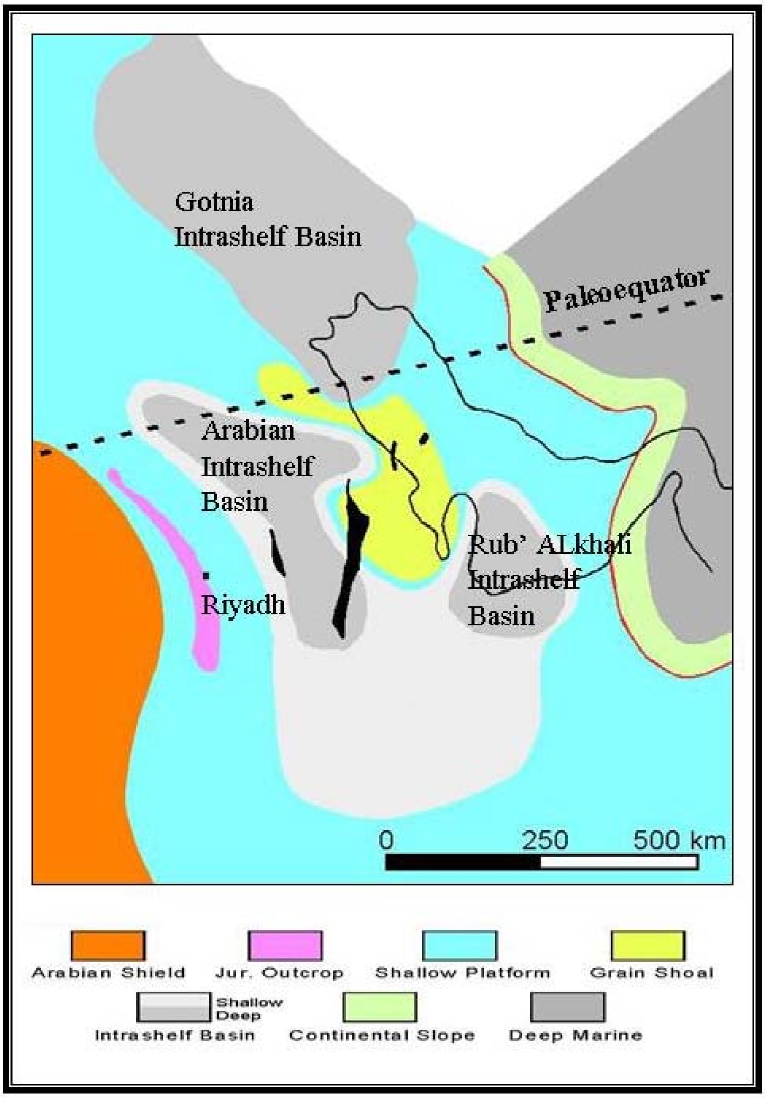

Figure 2.7. Jurassic paleogeography of Saudi Arabia and surrounding area. Compiled from Al Husseini (1997), Ayres *et al.* (1982), Koepnick and Waite (1991), and Murris (1980).

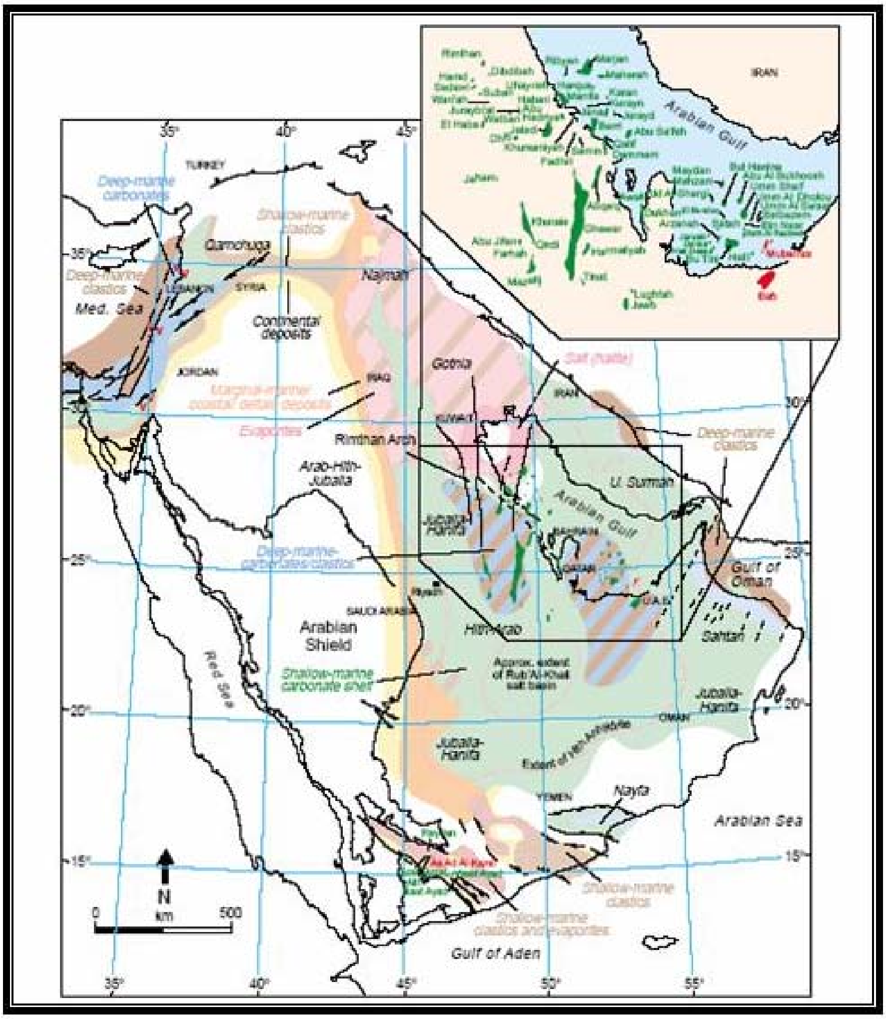

Figure 2.8: Regional depositional environments of the Arab and Hith Formation (Ziegler, 2001).

2.5. STRUCTURAL SETTING

2.5.1. INTRODUCTION

The main oil producing area of Saudi Arabia, which includes Khurais, Abqaiq, Ghawar, Qatif and Abu Safah fields, is located on the northeastern part of the Central Arabian arch. This arch is well expressed in the outcrop pattern of the Precambrian rocks and its younger sedimentary cover (Al-Hinai *et al*., 1997) to the west is the Arabian Shield, a vast complex of largely Precambrian igneous and metamorphic rocks (Pollastro *et al*., 1990). Bordering the shield to the east are the interior escarpments where long arcuate belts of Paleozoic, Mesozoic and lower Tertiary rocks crop out and dip basinward at about one degree or less (Powers, 1966). In eastern Arabia, almost flat-lying Tertiary and younger sediments of the Interior or Arabian Platform effectively cover and mask these older sediments (Powers *et al.,* 1966).

In the Arabian Shield area, the Precambrian and Early Cambrian north-west trending Najd fault trend (Schlumberger, 1975; Ayres *et al*., 1982;; Hancock *et al*., 1984; Al-Husseini, 2000 and Konert *et al*., 2001) is well developed (Figure 2.9). In contrast, mostly NNE-SSW striking, anticlinal trends and flexures reflecting deep-seated basement faults predominate to the east (Ayres *et al*., 1982; Al-Husseini, 2000), where the gently dipping, northeast-trending Abqaiq and Ghawar structures occur.

Drilling and seismic evidence support the presence, at depth, of large faults which bound basement blocks under the Ghawar structure (Wender *et al*., 1998; Konert *et a*l., 2001). These basement faults extend from the Precambrian metasedimentary basement up through the Paleozoic sediments and then die out in the Mesozoic section (Konert *et a*l., 2001). Broad flexuring of the post-Paleozoic sediments is the dominant structural style in eastern Arabia (Powers, 1968; Konert *et al*., 2001) and is exemplified by the En Nala anticline (Powers *et al*., 1966), along which occur Ghawar and other fields in eastern Arabia. Growth of the eastern Arabia fields structures such as Khurais, Ghawar and Abqaiq appear to have continued in the Late Cretaceous, with gentle regional compressive stresses being imposed on eastern Arabia in response to the closing of the Neo-Tethys Ocean (Beydoun, 1991; Nicholson, 2000, 2002). The most recent pulse of structural growth occurred between 20 and 40 million years ago when the Eurasian plate was welded onto the Arabian plate along the Zagros suture or "Crush Zone" (Goff et al**.,** 1995 and Beydoun, 1991). Minor faulting and/or fracturing, including the development of joints are found in the younger sediments, especially along the crests of the large flexures. These joints and lineaments are reported in the Hofuf Formation (Miocene-early Pliocene) in surface outcrops over Ghawar field (Hancock *et al*., 1984), and display two vertical joint sets; a dominant NNE to NE trending joint set and a NNW to NW joint set. These features may result from extension associated with the continuing vertical growth of the flexures (Figure 2.9).

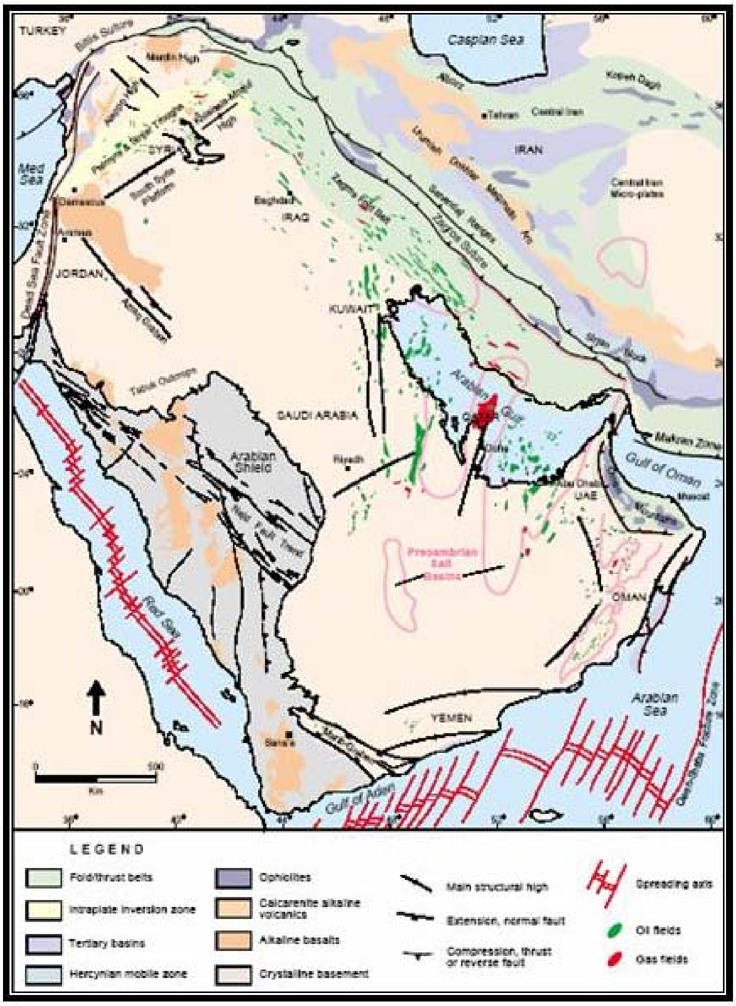

Figure 2.9. Major tectonic elements of the Arabian plate (Konert *et al*., 2001)

2.5.2. HOW INTRASHELF BASINS FORM

There are many explanations for the formation of intrashelf basins, but most of these basins appear to form on the shallow passive stable margins of plates. Here these shallow margins are extremely susceptible to the effects of marine transgression, particularly since in such settings tectonic subsidence tends to be minimal and the resulting sedimentary fill geometries are largely the products of sea-level variations (Aigner *et al.*, 1989). Often these Intrashelf basins develop as a result of a rapid eustatic sea level rise in which carbonate margins build up around an isostatically sagged deeper basin floor while the sedimentary fill lags at a slower rate of sedimentation (Read, 1985). As indicated above most intrashelf basins are short-lived and may be filled during the succeeding transgression event (Nassir, 2002). Three intrabasins (Arabian, Rub' ALkhali and Gotnia basins) all persisted until the latest Kimmeridgian, when each in turn became plugged with carbonates and evaporates resulting from restriction following falls in relative sea level.

2.5.3. INTRASHELF BASIN LOCATION AND EXTENT

The Qatar Arch separates the Arabian Basin (Figure 2.7) from the Rub' Al-Khali Basin to the south (Southern Gulf Basin of UAE and Qatar). The Rimthan Arch separates the Arabian basin from the Gotina Basin to the north (Kuwait and Iraq). During the upper Oxfordian and lower Kimmeridgian, these intrashelf basins were anoxic and the site of the accumulation of low –energy, organic rich lime mud (McGuire *et al.,* 1993).

2.6. SEQUENCE STRATIGRAPHY OF JUBAILA AND ARAB FORMATIONS.

Murris, (1980) recognized that the source rocks for the upper Jurassic Arabian reservoirs were deposited in an intrashelf basin on the Arabian Platform that was flooded by a major transgression initiated in the upper Middle Jurassic (late Oxfordian to early Kimmeridgian). These highstand carbonate deposits "kept up" with the rising sea level, finally surpassing the rate of rise and prograded seaward during the late stages of a sea level highstand. The late stages of the highstand (of the 2^{nd} order eustatic cycle) were characterized by increasingly more regressive deposits (the upper Jubaila and the Arab Formations) and were finally capped by extensive evaporates (the Hitth Formation) that accumulated during the arid climate of the next sea level lowstand.

CHAPTER THREE

METHODS AND TECHNIQUES

3.1 INTRODUCTION

The lithological characteristics of the Jubaila and Arab Formations have been well documented, together with the nature of the contact in surface locations. Unfortunately, as discussed earlier, the type section of Jubaila Formation is in surface locations and the Arab formation is in subsurface locations. In this chapter, the micropalaeontology, nannopalaeontology, petrography data and gamma values were selected to assist in clarifying the nature of this contact and assisting calibration and correlation of the contact from the surface exposures to the subsurface successions.

In order to address the aims of this study, we should illustrate and understand the potential controls on the depositionally induced heterogeneity present at the Jubaila-Arab formational contact. Fortunately through the years, Saudi Aramco has made an enormous number of Arab D thin sections from different fields and outcrop localities that can be used to address the Jubaila-Arab contact problem.

For the subsurface part of this study, eight wells have been selected from eight fields including Abu Safah (ABSF), Qatif (QTIF), Fzran (FZRN), Air Dar (ANDR), Shedgum (SDGM), Utmanyaih (UTMN), Hawyaih (HWYH) and Khurais (KHRS) (Figure 3.1) because of their geographic locations, almost full core recovery and also because of the readily available thin sections. Six of them also have nannopalaeotological data in Aramco corporate database (UTMN, HWYH, SDGM, FZRN, KHRS wells and the "diplomatic quarter" (DQ) section in the outcrop belt) (Figure 3.1). For the outcrops three localities were selected, which are Diplomatic Quarter (DQ) or Wadi Laban, Wadi Nissah (Okla Section) and the Helwah section.

Figure 3.1 shows the locations of all study wells from which samples were selected for detailed study and from three outcrop localities. Each of the various work phases in this study used subsets of this dataset. The DQ section is a 1 km road cut setting immediate west of Riyadh city and approximately 60 km south of the Jubaila Formation type section. It shows the entire Jubaila Formation and it has been selected because many recent studies gave detailed sedimentological prospective (Meyer and Price, 1993; Meyer *et al*., 1996 and Handford *et al*., 2002). Although the lower Arab Formation crops out along the Jurassic belt in central Saudi Arabia, the Jubaila-Arab boundary is exposed in very few localities, one of which is in the Wadi Nissah graben which located south of Riyadh. The Wadi Nissah area was considered as reference area for the upper Jubaila Formation (Powers *et al*., 1966), and it has a unique section of Jubaila-Arab contact informally called the Okla section. The Okala section and a section near Helwah have been selected for this study because preliminary field work indicated that the Jubaila top could be identified by the absence of the stromatoporoid facies (Okla, 1986; Le Nindre *et al*., 1990, Meyer, 1996 and Le Nindre, oral communication 2002).

Initial efforts to characterize this heterogeneity caused by depositional variation along the contact, include the following primary datasets:

١. Micropalaeontological data; thin sections analysis from core plugs of the Arab D reservoir in eight wells and from outcrop samples from three localities.

٢. Wireline log data to investigate any diagnostic character, particularly gamma ray, across the formational contact.

٣. Nannopalaeotological data; nannopalaeontology analysis from core plugs of the Arab D reservoir from study wells and from one outcrop locality.

٤. Petrographic data; to identify rock fabrics, textures and mineralogy and use this data to calibrate the sedimentological data markers across this contact.

Later efforts to address heterogeneity focused on micropalaeontological variation (biofacies) along the Jubaila-Arab formational contact from outcrop samples, where the contact is obvious, and apply these variation to the subsurface where positioning the contact is mostly unknown.

Finally, efforts to summarize and categorize the new biofacies and palaeoenvironment interpretations, upon which consistent recognition of the Jubaila-Arab formational contact is calibrated.

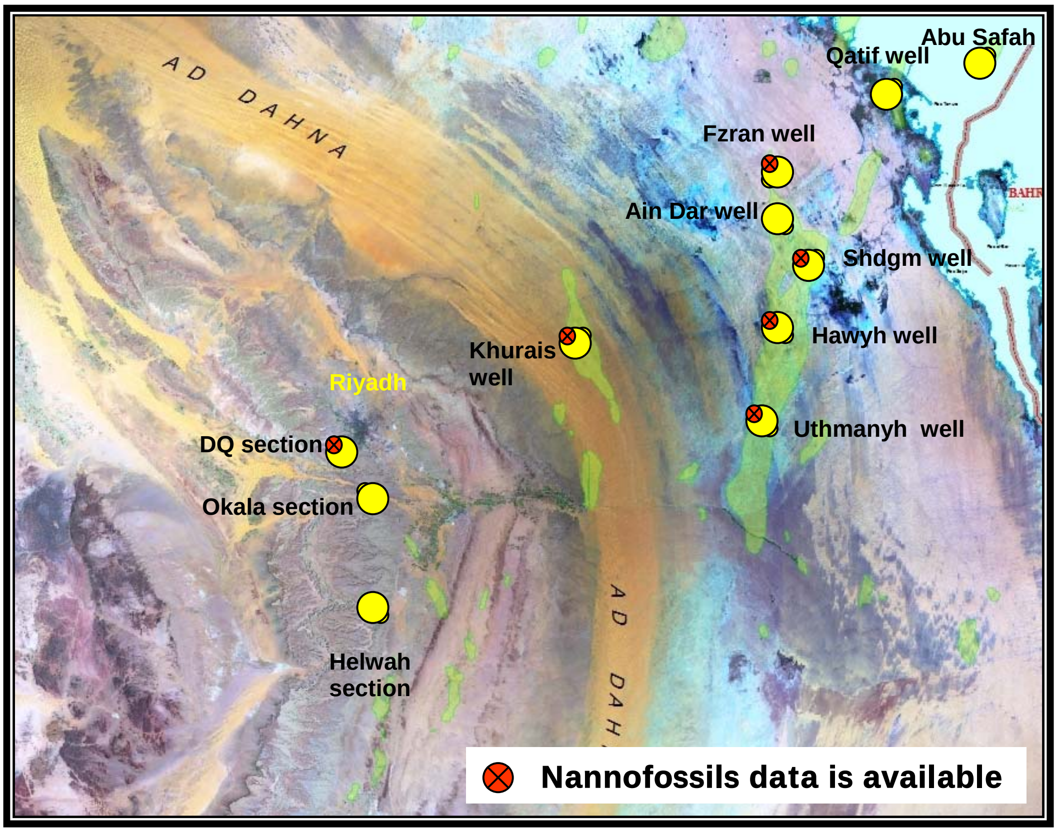

Figure 3.1. Outcrop and well locations

3.2. MICROPALAEONTOLOGICAL DATA

Micropalaeontological analysis was mainly used in this study, since it constituted one of the larger dataset available in the Arab D reservoir. It can produce a reliable dataset that is very useful for palaeoenvironmental and lithostratigraphic interpretation.

In this study micropalaeontological data came from approximately more than 3000 thin sections of 8 wells from Abu Safah, Qatif, Fazran, Shedgum, Ain Dar, Utmaniyah, Hwiyah and Khurais fields and outcrop samples from the Diplomatic quarter section immediately west Riyadh, Okla section in Wadi Nissah and Helwah section about 200 km south of Riyadh.

For the subsurface samples, thin sections were prepared from the trimmed ends of small core plugs drilled into the cores at 6 inch spacing. For the surface sections, samples were collected from every bed, and their positions measured carefully, and also photographed for ease of reference back in the laboratory (Figure 3.2). 647 thin sections that I have micropalaeontological analyzed for this thesis and most of thin sections had been analyzed for micropalaeontology by G. W. Hughes (Saudi Aramco) and others and saved in Aramco corporate database. Each micropalaeontological analysis has been interpreted to deduce the biofacies and depositional environment.

All identifiable biocomponents were recorded semi-quantitatively {present (1), rare (2-5), common (6-20) and abundant (>20)}. These biocomponents are predominantly benthonic foraminifera, but also include ostracods, calcareous algae and other fragments of macrofossils. The Hawiyah (HWYH) well was analyzed quantitatively to investigate if there was any difference in vertical distribution of biocomponents when recorded semi-quantitatively versus fully quantitatively. The distribution of the abundance of all identified species is displayed on a true-vertical scale on a StrataBugs chart (software for biostratigraphic corporate database), with lithology, interpreted palaeoenvironments and gamma logs (Enclosures 1 to 11).

The first and last downhole species occurrence, abundance and diversity are used to define biofacies. This data allows generation of palaeoenvironment maps for the Jubaila and Arab Formations based on their biofacies.

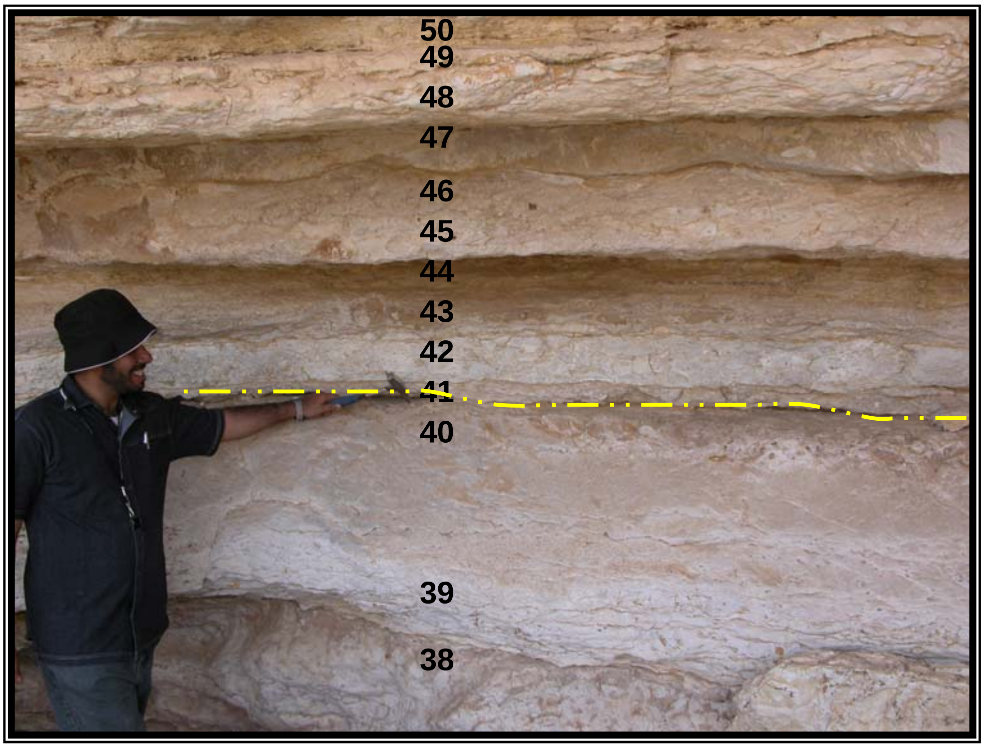

Figure 3.2. Jubaila-Arab Formations contact and sample numbers in Okla Section.

3.3. NANNOPALAEONTOLOGICAL DATA

As a means of potentially enhancing the value of the micropalaeontological data, calcareous nannopalaeontology was used. This new method for the region was made possible by quantitative analysis by Dr. Osman Varol (Varol Research) undertaken on behalf of Saudi Aramco. We use this data to (1) recognize correlative events, particularly long distance correlation, in order to diminish the influence of local depositional environment which give some confident and enhancement of our micropalaeontological data around the contact. (2) provide palaeoenvironmental evidence to test the idea that the Arab Formation was deposited mostly in restricted or protected environment and that the Jubaila was deposited in a setting characterized by open marine conditions. The presence of coccoliths, derived from planktonic organisms, can imply that the environment is open marine and from that we deduce the upwards limit of open marine influence, and indirectly approximate the Jubaila-Arab formational contact. The occurrence of ascidian spicules, nannofossils derived from benthic sea squirts, can also provide palaeoenvironmental and stratigraphic event information that suggest that the environment was restricted to shallow marine during the deposition of the Arab Formation. Nannopalaeontological data was available for five study wells and one outcrop locality in the Diplomatic Quarter (DQ). This data provide a robust framework for the correlation of the wells due to sparse data sampling typically prevents an adequate data and it also give very limited information in related to palaeoenvironment interpretation.

3.4. WIRELINE LOG DATA

Wireline logs were used in this study for the following reasons:

١. The Gamma Ray can indirectly provide some indication regarding the trend of relative sea level changes and cyclicity since it is affected by the variation of depositional environment, especially clay content. Diagenetic modification of the carbonates can, however, affect the gamma ray.

٢. Calibrate the logs character in the surface with biofacies, and establish a possible bioelectrofacies tool for extrapolating palaeoenvironments in uncored wells.

٣. Since wirelines constituted the largest single dataset available in Arab D reservoir, we should be able to possibly identify the formational contact all over the Saudi Arabia in uncored wells.

3.5. PETROGRAPHIC DATA

Simultaneously with the micropalaeontological analysis was the recoding of the important petrographic properties to:

١. Assist interpretation of the depositional environment, diagenetic features and mineralogy.

٢. Help us to see where the storm pulses dominated in the study sections such as a combination of the shallow biocomponents and intraclasts within the deep environment strongly suggest that biocomponents were transported from upward section.

٣. Verify that the barren sections in this study are due to depositional environment or diagenesis overprint and if the barren sections are due to the depositional environment no other way to prove whether the barren sections were deposited in so restricted or anoxic environment.

CHAPTER FOUR

MCROFOSSIL GENERA AND PALAEOENVIRONMENT

4.1. MICROFOSSIL GENERA IN JUBAILA AND ARAB FORMATIONS

4.1.1. INTRODUCTION

This section provides a brief review of the composition, taxonomy, characteristics and occurrence of type species of the important species in the Jubaila and Arab Formations in Saudi Arabia.

In this type of micropalaeontological study, it is essential that the correct taxonomy is applied and that the most significant references are also documented for future use by specialists. The taxonomy references are not in the thesis references list because all these sources are historical references for the purpose of detailed taxonomic investigation, beyond the scope of this thesis.

4.1.1.1. Abbreviations and Latin Terms

art.: article, generally with reference to the *International Code of Zoological Nomenclature*.

BMNH: British Museum (Natural History), London.

DSDP: Deep See Drilling Project.

e.: east, eastern.

err.cit.: erroneous citation, including typographic errors and other forms of intentional or unintentional misspelling.

err. emend.: erroneous emendation, contrary to the rules of the ICZN.

fide: according to.

ICBN: *International Code of Botanical Nomenclature*.

ICZN: *International Code of Zoological Nomenclature*.

L.: Lower.

M.: Middle.

MNHN: Museum National d'Histoire Naturelle, Paris.

Ms.: manuscript.

N.: North, northern.

nec.: nor.

nom.conserv.: conserved name, by action of the International Commission on Zoological Nomenclature.

nom.corr.: corrected name [for..].

nom.imperf.: imperfectly formed name, automatically correctable according to the ICZN.

nom.nud.: nomen nudum, nude name, without description or otherwise unavailable.

nom.nov.: nomen novum, new name.

nom. prov.: provisional name, unavailable according to the ICZN.

nom.reject.: rejected name, by action of the International Commission on Zoological Nomenclature.

nom.subst.: nomen substitutum, name proposed to replace that of a junior homonym

nom.superfl.: superfluous name; invalidly including a previously proposed name.

nom.transl.: nomen translatum, name transferred to a different rank in the classification, as from genus to subgenus, or subfamily to family.

nom.vernac.: vernacular name, not Latinized, hence not available.

non.: not

obj.: objective synonym; genus proposed with the same type species as that of an earlier described genus.

OD: original designation, fixation of type species of genus by original citation.

OD (M): original designation (monotype): fixation of type species of genus by monotype but not explicitly so stated.

Op.: opinion, with reference to Decisions and Opinions of the International Commission on Zoological Nomencalature.

opp.: opposite.

Partim.: part; term used with resticted meaning.

pers.comm.: personal communication.

pro.: for.

ref.: reference.

S.: South, southern.

SD: subsequent designation, fixation of type species of genus by later author, when not fixed in the original description.

SD(SM): subsequent designation (subsequent monotype), fixation of type species of genus by monotype in later paper, when no species were originally included.

SEM: scanning electron microscope (or photograph).

subj.: subjective.

syn.: synonym.

TEM.: transmission electron microscope (or photograph).

U.: Upper.

USNM: United States National Museum.

W.: West, western.

4.1.2. FORAMINIFERA

Single-celled protozoans, comprising a very complex group of organisms, with 12 suborders recognized by Loeblich and Tappan (1984) and some 60-80,000 species identified from Phanerozoic strata. As many shapes, sizes, and wall-structures exist, this thesis can provide only minimal information needed to identified the important Late Jurassic genera.

4.1. 2.1. Benthonic Foraminifera

As planktonic foraminifera had not evolved during the Late Jurassic here considered, only benthonic foraminifera were available as foraminiferal sediment producers. Even if planktonic had existed, it is almost certain that they would have been environmentally excluded from the shallower Arab Formation. The benthonic foraminiferal assemblages recorded within Jubaila and Arab Formations are predominantly those that have an agglutinated test, although calcareous walled forms are also present.

4.1.2.1.1 Agglutinated Foraminifera. The foraminifera test of agglutinated foraminifera is formed by an outside material attached to the organic membrane and they make use of the available material of the sea bed indiscriminately, including sand grains, sponge spicules, mica flakes, coccoliths, diatoms and heavy minerals.

The remains of both larger and smaller agglutinated foraminifera occur throughout the sections of the upper Jurassic including the Jubaila and Arab formations. Such forms comprise the most widespread and occasionally the dominant foraminiferal group within the samples examined. Differentiation between larger and smaller agglutinating forms is important for precise palaeoenvironmental interpretation. They are therefore considered separately here.

4.1.2.1.1.1 Larger agglutinated foraminifera.Larger agglutinated foraminifera are relatively common throughout the Arab D reservoir although the assemblage recorded is quite restricted composed primarily of common *Kurnubia* palastiniensis, *Mangashtia viennoti*, *Pfenderina salernitana* and less common *Alveosepta jaccardi*, together with rare *Everticyclammina spp*., and *Pseudocyclammina spp.*

Pfenderina Henson, 1948

(Plate 1, figures 1-6; Plate 2, figures1 to 3)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Ataxophragmiacea

Family : Pfenderinidae

Sub Family : Pfendernininae

Genius : *Pfenderina*

*Type species**:** Eorupertia neocomiensis* Pfenderina, 1938 p.236; OD.*Pfenderina* Henson.1948**,** p. 609.

1962 *Pfenderina neocomiensis* (Pfender), 1962; Smout & Sugden: 585, pl.73.

1962 *Pfenderina salenitana* Sartoni & Crescenti, 1962, pl.16; pl.17, figs.1-7.

1988 *Paleopfenderina salernitana* (Sartoni & Crescenti); Septfontaine: 245.

Diagnosis: Test a high trochospiral, chambers numerous, surrounding an axial region of thickened shell material, septa perpendicular to the spiral axis, and oblique to the test axis; wall microgranular in structure, imperforate; aperture consisting of numerous pores in the center of the apertural face, with secondary intercameral foramina about equidistant from the ends of the chambers, appearing along the central solid column as a spiral groove or subcameral tunnel. U. Jurassic to U. Cretaceous (Cenomanian); Europe; SW Asia.

Remarks: The genus Pfenderina was erected by Henson (1948b) with *Eorupertina neocomiensis* Pfender (1938) as type species. "The description…[of *Pfenderina*]…is based mainly on Pfender's figures of *E.neocomiensis* checked against observations of random sections of the same, or a very similar, species occurring in the Middle East". It is these latter specimens and those figured by Smout & Sugden (1962) from Qatar (as *P. neocomiensis*) that are here referred to *P.salernitana*. Both *P.salernitana* and *P.trochoidea* Smout & Sugden are referred by Septfontaine (1988) to his new genus *Paleopfenderina* (the former being the type-species). However, we consider the criteria cited by Septfontaine to separate *Paleopfenderina* from *Pfenderina* to characterize differences between species, not genera.

Mangashtia Henson, 1948

(Plate 2, figures 4 to 6; Plate 3, figures 1 to 4)

Order: Foraminiferida

Super family: Cyclolinacea

Family: Cyclolinidae

Subfamily: Cyclopsinellinae

Genius: *Mangashtia*

Type species: *Mangashtia viennoti* Henson, 1948; OD.

1948 *Mangashtia* Henson, p.94.

Diagnosis: The provisional description was based on random and fragmentary sections, from Cenomanian-Turonian limestones of Iran, but many essential characters are not described and the genus is unrecognizable pending description of better and more complete material.

Remarks: The original description of Henson (1948c) was based on random and fragmentary sections and as a result the taxon is little known and was placed in "Genera of Uncertain Status" by Loeblich & Tappen, 1988. Further examination of the syntypes now suggests that they are, in fact, subaxial (tangential) sections through *Biplanata peneropliformis* Hamaoui & Saint-Marc (1970), described and well-illustrated from the Cenomanian of Israel and Lebanon (see also Hamaoui in Schroeder & Neumann, 1985). Fourcade *et al.* (1997) revised *Mangashtia* from "topotypic" material in the Museum

National d’Histoire Naturelle, Paris (they appear not to have seen the syntypes in the BMNH), but their material comes from higher in the tan-i-Kurd section (early Turonian) and on first examination, does not appear to be conspecific (or congeneric) with Henson’s taxon Curiously, in the late Cenomanian part of the same section (op. cit.) are said to occur limestones with *Biplanata peneropliformis* Clearly, his taxon needs yet further investigation.

Stratigraphic range & distribution:

Within the mid-Cenomanian-mid-Turonian.Cenomanian/Turonian, Iran (Henson, 1948c); late Middle-Late Cenomanian, southern Iraq and Persian Gulf (Riche & Prestat, 1980); Natih Formation, Oman Mountains (Smith *et al.*, 1990; Kennedy &Simmons, 1991); Mishrif Formation, Abu Dhabi (Alsharhan & Kendall, 1991); Cenomanian, Israel and Lebanon (Hamaoui & Saint-Marc,1970).

Alveosepta Powersi, 1967

(Plate 3, figures 5 and 6; Plate 4, figures 1-3)

<u>Order</u>: Foraminiferida

<u>Sub Order</u> : Textulariina

<u>Super Family</u> : Loftusiacea

<u>Family</u> : Hottingeritidae

Genius: *Alveosepta*

Type species: Cyclammina jaccardi Schrodt, 1894**,** p. 734; OD.

1964b *Paeudocyclammina powersi* Redmond: 406, pl.1, figs 5-8; pl.2, figs 5-8.

1967 *Alveosepta* Hottinger**,** p. 79, 84.

1967 *Alveosepta Powersi* (Redmond), Hottinger: 81, pl.1, fig.15; pl.16, fig. 20.

Diagnosis: Test coiled, microspheric early stage streptospirally, megalospheric test and microspheric adult planispiral, adult may tend to uncoil; wall agglutinated, exoskeleton with subepidermal network lining apertural face and septa as well as lateral and peripheral chamber walls, some species may have an exoskeletal projection that forms a median lamella, partially or completely bisecting the chambers; aperture consists of large openings at the base of the apertural face, supplementary areal foramina may be produced by resorption of the epidermal layer of the septum, allowing the alveoles to open into the adjacent chamber.

Remarks: the type specimens from the Upper Jubaila Formation (Early Kimmeridgian) of Saudi Arabia (in the American Museum of Natural History, New York) are re-figured here. For a revision of the species, emendation of the genus *Alveosepta* and description of the new subgenus *Redmondellina*, see Banner& Whittaker (1991).

Stratigraphic range & distribution:

Early Kimmeridgian-early Tithonian. Upper Jubaila Formation, Saudi Arabia (Redmond, 1964b; Powers et al.,1966; Powers,1968); Amran Formation, Yemen (Simmons & Al-Thour,1994); Early Kimmeridgian (Banner & Whittaker, 1991); Arab D-C, offshore Abu Dhabi (Al-Silwadi *et al.*, 1996).U. Jurassic (Oxfordian to Kimmeridgian); Switzerland; France; Portugal; Morocco

Everticyclammina Redmond, 1964

(Plate 4, figures 4-6)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Loftusiacea

Family : Cyclamminidae

Sub Family : Buccicrenatinae

Genius : *Everticyclammina*

Type species: Everticyclammina hensoni Redmond, 1964 = *Cyclammina greigi* Henson, 1948, p. 13; OD.

1964 *Everticyclammina* Redmond, p. 407.

1965 *Pseudobaculites* Maync, p. 39 (non *Pseudobaculites* Cobban, 1952).

1943 *Pseudocyclammina virguliana* Koechlin, p. 195; OD. *Mayncella* Banner, 1966, p. 206.

1948 *Cyclammina greigi* Henson, p. 13; OD.

Diagnosis: Test planispirally enrolled and involute, lenticular to slightly compressed, later with a slight tendency to uncoil, chambers wedge like, sutures radial, slightly curved; wall agglutinated, alveolar, septa short and not alveolar, the elongate areal aperture resulting in very short septa, but with the triangular to rectangular thickened base of the septal face remaining against the previous whorl as seen in median section; aperture a short vertical areal slit.

Remarks: The aperture and wall characters, as well as the synonymy for this genus were discussed by Loeblich and Tappan (1985, p. 100). It differs from *Buccicrenata* in having a less compressed test, a simple slitlike aperture rather than an elongate zigzag slit, wedgelike rather than reniform chambers, and more extensive secondary deposits connecting the bases of successive septa against the previous whorl.

Stratigraphic range & distribution;

U. Jurassic (U. Oxfordian) to U. Cretaceous (Cenomanian); Saudi Arabia: Qatar Peninsula; Switzerland: France

Pseudocyclammina Yabe and Hanzawa, 1926

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Loftusiacea

Family : Cyclamminidae

Sub Family : Choffatellinae

Genius : *Pseudocyclammina*

Type species: Cyclammina lituus Yokoyama, 1890**,** p. 26; OD.

1925 *Choffatella cyclamminoides* Silvestri: 450, pl.1, figs 1-3.

1926 *Pseudocyclammina* Yabe and Hanzawa,10, pl.2, figs 3-6.

1964b *Paeudocyclammina Sulaiyana* Redmond: 407, pl.1, figs 9-11; pl.2, fig.9.

Diagnosis: Test planispirally enrolled or rarely streptospiral in the early microspheric stage, sub-spherical to flattened, involute at least in early stage, later uncoiling, sutures strongly oblique in coiled stage; wall coarsely agglutinated, with coarse subepidermal network, exoskeleton may have a few irregular pillars in a narrow zone in the median plane of the test; endoskeleton consisting of thick and massive septa, perforated by large openings; aperture areal, cribrate, covering the apertural face.

Remarks: Banner& Whittaker (1991), in their revision of Redmond's (1964) "new lituolid foraminifera" from Saudi Arabia, showed that his *P. sulaiyana* was synonymous with *P. lituus*. In the same paper it is commented on that *Pseudocyclammina*, like *Bramkamella*, had large alveoles (several times wider than in *Chofatella*) are found in clear limestones, largely free of argillaceous sediment, and are often associated with dasyclad and codiacean algae. Although *Pseudocyclammina* has a long fossil record it is nevertheless only found whenever and wherever the appropriate palaeoenvironment was existed.

Stratigraphic range & distribution:

Late Oxfordian– within the early Aptian. Basal Cretaceous, Iran, Iraq, Qatar (Henson, 1948c); Gargagu, Sarmord, Yamama/Sulaiy formations of Iraq, Sulaiy Formation, Iraq, Kuwait, Qatar, Saudi Arabia (Owen & Nasr, 1958; van Bellen et al., 1959; Al-Naqib, 1967, Sugden & Standring, 1975; Banner & Whittaker, 1991); Neocomian Limestone, Musandam (Hudson & Chatton, 1959); Surmeh, Fahliyan-

Dariyan formaitions, S.W. Iran (James & Wynd, 1965; Sampó, 1969; Setudehnia, 1972; Kalantari, 1982); Zones V?, II-I (lowermost), southern Iran (Gollesstaneh,1974); Habshan-Lekhwair formations, Arabian Peninsula and Gulf (including Abu Dhabi (Hassan et al., 1975; Alsharhan & Nairn, 1986; Alsharhan & Kendall, 1991); Berriasian (Ibrahim,1975); Late Valanginian-Hauterivian, northern Iraq (jones, 1996) [as *P. lituus*]. Sulaiy-Yamama Formations, Saudi Arabia, Qatar (Redmond, 1964b; Powers et al., 1966; Powers, 1968; Sugden & Standring, 1975) [as *P. sulaiyana*].

L. Jurassic (Domerian) to U. Cretaceous (Coniacian); Morocco; Libya; France; Italy; Poland; Yugoslavia; USSR: Ukraine

Kurnubia Henson, 1948

(Plate 5, figures 1-6; plate 6, figure 1-2)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Ataxophragmiacea

Family : Pfenderinidae

Sub Family : Kurnubiinae

Genius : *Kurnubia*

Type species: Kurnubia palastiniensis Henson, 1948 (syn.: *Valvulinella jurassica* Henson, 1948, p. 607); OD.

1948 *Kurnubia* Henson, p. 608.

Diagnosis: Test elongate, early chambers trochospiral about a central column with chambers some-what inclined to the axis of coiling, later uncoiled, uniserial, and rectilinear, outer part of chambers has a characteristic subepidermal network, central part with endoskeletal pillars that are continuous from chamber to chamber, spaces between pillars later filled secondarily to produce a central column; apertural face consists of a plate over the umbilical region with many small apertures interspersed between pillars, where apertures are secondarily filled to produce a column, the septum adjacent to the column is resorbed to form a secondary foramen.

Stratigraphic range & distribution:

L. Jurassic (Lias) to U. Jurassic (Kimmeridgian); SW Asia; Morocco; Yugoslavia; Crete.

Ammobaculites Cushman, 1910

(Plate 6, figures 3-4)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Lituolacea

Family : Lituolidae

Sub Family : Ammomarginulininae

Genius : *Ammobaculites*

Type species: Spirolina agglutinans d'Orbigny, 1846, p. 137; OD.

١٩١٠ *Ammobaculites* Cushman, p. 114.

Diagnosis: Test free, elongate, early portion close coiled, later uncoiling and rectilinear, rounded in section; wall coarsely agglutinated, interior simple; aperture terminal, rounded.

Remarks: A specimen of *Spirolina agglutinans* in the d'Orbigny Collection, MNHN, Paris, was designated as lectotype of the species and illustrated (Loeblich and Tappan, 1964, p. C241). Thus the later designation of a specimen in the Vienna Museum (GBA 1981/03/196) as lectotype (Papp and Schmid, 1985) is invalid.

Stratigraphic range & distribution:

L. Mississippian (Kinderhookian) to Holocene; cosmopolitan.

Nautiloculina Mohler, 1938

((Plate 12, figures 3-6; Plate 13, figures 1-2)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Lituolacea

Family : Nautiloculinidae

Genius: *Nautiloculina*

Type species: Nautiloculina oolithica Mohler. 1938; OD.

1938 *Nautiloculina* Mohler, *p.* 18.

Diagnosis: Test free, lenticular in form, planispirally enrolled and involute, globular proloculus followed by numerous small chambers per whorl that increase gradually in size, interior simple, sutures radial to very slightly arched; wall microgranular calcareous. Agglutinated commonly diagenetically altered, foreign material more abundant in outer whorls of some species, structure simple, no. subepidermal network or other exoskeletal or endoskeletal structures present, wall single layered, but septa secondarily doubled by addition of a second wall layer over the previous apertural face as a new chamber is added, umbonal region also progressively thickened as chambers are added; aperture equatorial, a low interiomarginal arch. U. Jurassic (L. Malm) to L. Cretaceous (Bedoulian); Switzerland; France: Yugoslavia; USSR: N. Caucasus; Egypt; Israel.

4.1.2.1.1. 2. Smaller agglutinated foraminifera**.** The assemblage of smaller agglutinated foraminifera is quantitatively dominated throughout Arab D reservoir by small bi-and triserial forms assigned to the category of chrysalindinid juveniles. Larger specimens may be further identifiable as *Redmondoides lugeoni* and *Praechrysalindina* spp. Other forms include occasional *Haplophragmoides* spp. *Verneuilina minuta* spp. and occasional to common inflated, siphonate forms assigned to the genus *Siphovalvulina*.

Eggerella Cushman, 1935

<u>Order</u>: Foraminiferida

<u>Sub Order</u> : Textulariina

<u>Super Family</u> : Textulariacea

<u>Family</u> : Eggerellidae

<u>Sub Family</u> : Eggerellinae

Genius : *Eggerella*

Type species: Verneuilina bradvi Cushman, 1911**,** p. 54; OD.

*Eggerella Cushman. 1933***,** p. *33.*

1963 *Alyarezina* Bermdez *and Rivero.*, p. *266;* type *species: Verneuilina mexicana* Nuttall, 1932*,* p. *6;* OD.

Diagnosis: Test subconical, early stage in trochospiral coil of five inflated chambers per whorl, at least in the microspheric generation, later reduced to three chambers per whorl; wall finely agglutinated, commonly of calcareous particles on a proteinaceous base, canaliculate, the pores with an organic lining; aperture a low slit near the base of the apertural face, bordered by a narrow lip.

Stratigraphic range & distribution: Jurassic to Holocene; cosmopolitan.

Redmondoides Septfontaine, 1977

(Plate 6, figures 1-2; Plate 7, figures 1-6; Plate 8, figures 1-6; Plate 9, figure 1)

Order: Foraminiferida

Sub Order : Textulariina

Genus: *Redmondoides*

Remarks: this species was revised by Banner *et al.,* 1991, using metatypic material from the Bathonian/Callovian of Haute-Savoie, France and from offshore Abu Dhabi (the latter from the BP reference Collection).

Stratigraphic range & distribution:

Early Bajocian-latest Oxfordian. Araej Formation, (lower) Izhara member, Offshore Abu Dhabi (Banner *et al*., 1991), Amran Formation (Later Callovian?-Oxfordian), Yemen (Simmons & Al-Thour, 1994).

Vulvulina d'Orbigny, 1826

(Plate 9, figure 2-5)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Spiroplectamminacea

Family : Spiroplectamminidae

Sub Family : Vulvulininae

Genius : *Vulvulina*

Type species: Vulvulina capreolus d'Orbigny, 1826 = *Nautilus (Orthoceras) pennatula* Batsch, 1791, No. 13, pl. 4, figs. 13a-d.; SD Cushman, 1928, p. 118.

1826 *Vulvulina* d'Orbigny, p. 264. *Schizophora* Reuss,1861, p. 12; type species: *Schizophora neugeboreni* Reuss, 1861; OD (M).

1870 *Venilina* Gûmbel, p. 648; type species: *Venilina nummulina* Gûmbel, 1870; SD Cushman, 1928, p. 118.

1902 *Trigenerina* Schubert, p. 26: type species: obj.; SD (SM) Liebus, 1911, p. 930. *Bigenerina (Valvulina)* Yabe and Hanzawa, 1929, p. 154 (nom. transl., err. cit. pro *Vulvulina).*

Diagnosis: Test free, flaring or broad and elongate, lozenge shaped to rhomboidal in section, margins sharply angled, early portion planispirally coiled at least in the microspheric generation, later with very broad and low, biserially arranged chambers that are strongly curved backwards toward the proloculus, and in well-developed specimens may be uniserial in the final stage, sutures distinct; wall finely agglutinated, surface smoothly finished; aperture a broad low interiomarginal arch in the early stage, later becoming terminal, a narrow elongate slit.

Stratigraphic range & distribution:

U. Jurassic? U. Cretaceous (Campanian); Paleocene to Holocene; cosmopolitan.

Textularia Defrance, 1824

(Plate 9, figure 6)

<u>Order</u>: Foraminiferida

<u>Sub Order</u> : Textulariina

<u>Super Family</u> : Textulariacea

<u>Family</u>: Textulariidae

<u>Subfamily</u>: Textulariinae

Genus: *Textularia*

Type species: *Textularia sagittula* Defrance in de Blainville, 1824; OD (M).

1824 *Textularia Defrance* in de Blainville, p.177. *Textularia Ehrenberg*, 1839, opp. P.120 (err.emend.).

1979 *Textella Mikhalevich*, p.17; type species: *Textularia foliacea* Heron-Allen and Earland var. occidentalis Cushman, 1922, p. 976 (non *Textularia sagittula* var.fistulosa Brady, 1884) = *Textularia valeriae* Loeblich and Tappan, nom,nov.,herein;OD.

1975 *Vulvulinella Saidova*, p. 121(err. Cit.as valvulinella on pl.39, fig.8 non *Valvulinella Schuber,* 1907); type species:*Textularia milletti* Cushman, 1911, p.13;OD.

Diagnosis: Test biserial throughout or may have an adcentitous third chamber against the first pair of chambers in the microspheric generation; wall agglutinated, traversed by canaliculi that may open as perforations or be closed externally by a thin agglutinated layer and typically are closed internally by the organic lining of the test: aperture a low arch or slit at the base of the apertural face. cosmopolitan.

Remarks: the agglutinated grains in the wall of *Textularia aegyptica* Said, 1949 are held in a calcareous fine-grained cement, the randomly oriented grains being equidimensional and about 0.2µ m to 0.4 µm in diameter, according to Toksvad and Hansen (1983, p.161).

Stratigraphic range & distribution: Pennsylvanian to Recent

Praechrysalidina Luperto Sinni, 1979

(Plate 10, figure 1)

Order: Foraminiferida

Sub Order : Textulariina

Super Family : Ataxophragmiacea

Family : Ataxophragmiidae

Sub Family : Ataxophragmiinae

Genius : *Praechrysalidina*

Type species: Praechrysalidina infracretacea Luperto Sinni, 1979; OD.

Praechrysalidina Luperto Sinni, 1979, p. 4.

Diagnosis: Test conical, triserial throughout, rarely with incipient rafters behind the apertural face; wall calcareous, thick, microgranular, dark, at high magnification appearing to be crossed by fine striae aligned perpendicular to the test surface, the striae particularly evident in the region corresponding to the marginal zone, agglutinated material sparse; aperture terminal, cribrate, of numerous pores restricted to a well-defined area that is inclined toward the test axis and surrounded by a peripheral undivided marginal zone.

Stratigraphic range & distribution: L. Jurassic to L. Cretaceous Italy.

4. 1. 2. 1. 2. Calcareous Benthonic Foraminifera. The test is formed by an organic membrane composed of the calcareous inner lining wall.

The occurrence and distribution of calcareous benthonic foraminifera is found to be variable within the Arab D reservoir investigated.

Nautiloculina oolithica is common to occasional throughout Arab D reservoir and within the 8 wells representing the sections of Arab D reservoir investigated. Within these wells, low-spired forms of the genus *Trocholina* which is *Trocholina alpina* quantitatively predominate, with high-spired forms assignable to *Trocholina palastiniensis* being very much rare. *Lenticulina spp. and nodosarids are only infrequently recorded.*

Nodosaria Lamarck, 1812

Order: Foraminiferida

Sub Order : Lagenina

Super Family : Nodosariacea

Family : Nodosariidae

Sub Family : Nodosariinae

Genius: *Nodosaria*

Type species: *Nautlus radicula Linne, 1758, p.711; SD(SM) Lamarck, 1816, p. 465.*

1812 *Nodosaria* Lamarck**,** p.121.

1900 *Glandulonodosaria* A. Silvestri**,** P.4; type species*: Nodosaria ambigua Neuegeboen,* 1856**,** p.71; (M).

Diagnosis: Test elongate, multilocular, ovate proloculus followed by uniserial and rectilinear globular to ovate chambers; wall calcareous, hyaline, perforate, surface smooth and unornamented; aperture terminal, radiate or rounded and bordered by radiating grooves, produced on a neck. L. Jurassic to Holocene; cosmopolitan.

Trocholina Henson, 1948a

(Plate 13, figure 6; Plate 14, figures 1-4)

<u>Order</u>: Foraminiferida

<u>Sub Order</u> : Involutinina

<u>Family</u> : Involutinidae

<u>Subfamily</u>: Involutininae

Genius: *Trocholina*

Type species: *Involutina conica* Schlumberger, 1898**,** p.151; SD Cushman, 1933**,** p.231.

1922 *Trocholina Paalzow***,** P.10.

1956 *Neotrocholina Reichel***,** p.404; type species: Neotrocholina valdensis Reichel, 1956; OD.

1957 *Trocholina* (*Trochonella) Kristan***,** p.285; type species: *Trocholina (Trochonella) crassa* Kristan, 1957; OD.

1966 *Ichnusella* Dieni and Massari, p.170; type species: *Ichnusella trocholiaeformis* Dieni and Massari, 1966; OD.

Diagnosis: Test conical, globular proloculus followed by trochospirally enrolled tubular second chamber, all whorls visible on the convex spiral side, around the wide umbilicus that contains nodes and pillars of lamellar structure, one lamella deposited at the formation of each whorl of the enrolled tubular chamber; wall coarsely perforate on the umbilical side; aperture at the end of the tubular chamber.

Remarks: the holotype (matrix-free specimen) and most of the paratypes are very poorly preserved (dolomitized?).

Stratigraphic range & distribution:

Early Bajocian-late Tithonian (early part). Trocholina Limestone, Musandam (Hudson & Chatton, 1959); Najmah Formation, Iraq (van Bellen *et al*., 1959); Jurassic, Yemen (Beydoun, 1960); Shuqra Formation, Yemen-Dhofar (Beydoun,1966); Hisyan Member, Dhruma Formation and Tuwaiq Mountain Formation, Saudi Arabia (Powers *et al.,* 1966; Powers,1968; Moshrif, 1987; Jones, 1996); Surmch Formation, S.W. Iran (Setudehnia, 1972; Kalantari, 1982); Zones IX (uppermost)-VI (lowermost), southern Iran (Gollesstaneh, 1974); Araej Formation, Qater (Sugden & Standring, 1975); Araej and Arab D, B and A formations, Arabian Gulf (Alsharhan & Whittle, 1995a, 1995b); late Callovian, Palestine/Israel (Henson, 1948a fide Maync, 1966).

<u>4.1.2.1.3. Miliolids</u>**.** The major groups of calcareous genera were distinguished as porcelaneous according to their appearance in reflected light, and dark appearance in reflected light.

Quinqueloculina spp. foraminifera are recorded within all of the wells of Arab D reservoir examined, their overall observed occurrence being in very high numbers in upper part of Arab D reservoir. Their occurrence is, however, observed to be sporadic throughout the lower part of Arab D reservoir.

Quinqueloculina d'Orbigny, 1826

(Plate 15, figures 5-6; Plate 16, figures1 -5)

<u>Order</u>: Foraminiferida

<u>Sub Order</u> : Miliolina

<u>Super Family</u> : Miliolacea

<u>Family</u> : Hauerinidae

<u>Sub Family</u> : Haueridae

Genius : *Quinqueloculina*

Type species: Serpula seminulum Linné, 1758, p. 786; SD Parker and Jones, 1859, p. 480.*Quinqueloculina* d'Orbigny, 1826, p. 301 (on Official List of Generic Names in Zoology, ICZN Op. 692, China, 1964, 587, p. 26).

1798 *Frumentarium* Fichtel and Moll, p. 16 (nom. reject, ICZN Op. 692, China. 1964, p. 26).

1859 *Multiloculina* Abich, p. 105. 150; type species: *Serpula seminulum* Linné, 1758, SD Loeblich and Tap-pan, 1964, p. C458.*Trillina* Munier-Chalmas, 1882, p. 424; type species: *Triloculina strigillata* d'Orbigny, 1850, *p.* 409; OD.

1984 *Rumanoloculina* Neagu, p. 83; type species: *Quinqueloculina robusta* Neagu, 1968, p. 566; OD.

Diagnosis: Test ovate in outline, early chambers quinqueloculine in both microspheric and megalospheric generations, or may be quinqueloculine, depending on the degree of overlap of successive chambers, chambers one-half coil in length, added in planes of coiling that are 72° apart, successive chambers added 144° apart, commonly with five chambers visible at the exterior, of which four are visible from one side and three from that opposite, chambers with floors at least in the mature stage; wall calcareous, imperforate, porcelaneous; aperture ovate, flush with the surface, provided with a bifid tooth.

Stratigraphic range & distribution: Triassic to Holocene; cosmopolitan.

4.1.3. BENTHONIC CALCAREOUS ALGAE

A brief review of the occurrence and composition of the benthic marine calcareous algal assemblage recorded within Arab D reservoir examined is given below.

4.1.3.1. Dasycladacean algae (Calcareous green algae)

Clypeina FAVRE

(Plate 16, figure 1; Plate 17, figures 1-6; Plate 18, figure 1)

Phylum: Chlorophyta

Family: Dasycladaceae

Tribe: Clypeineae

Genius: *Clypeina*

1927 *Clypeina jurassica* Favre: 34, pl.1, figs.2-3.

1932 *Clypeina jurassica* Favre: J.Favre: 12, test-figs.10-11.

1951 *Clypeina jurassica* Favre: J. Morellet: 399, pl.22.

1955b *Clypeina jurassic*a Favre and C. hanabatensis Yabe & Toyama; Elliott: 125.

1958a *Clypeina jurassica* Favre: Donze: 21.

1962 *Clypeina jurassica* Favre: Powers: 131.

1991 *Clypeina sulcata* Granier and Brun.

Diagnosis: Flat, saucer-, bowl- or funnel-shaped calcareous discs formed of horizontally-fused radial tubes: centrally they meet in a stout calcareous ring, each tube communicating by a single pore with the central cavity: the central ring is thickened below by the fused bases of the radial tubes and sometimes a smaller similar feature shows on the upper surface. In life these were the calcified structures of fertile dasyclad whorls.

Clypeina occurs as small fossil calcareous discs, saucer-, bowl- or funnel-shaped, centrally perforate, and with the solid portion composed of fused radiating tubules: communicating each by a single core with the central cavity. Usually the discs are separate, but occasionally several occur together in vertical, consecutive association. Described by Michelin (1845) from the French Oligocene as a coral, it was subsequently referred to other marine invertebrate groups by various authors until Munier-Chalmas (1877), in a brief communication, drew attention to its true algal nature.

Clypeina was reconstructed from Eocene material to show the probable structure and appearance of the plant in life (Morellet & Morellet, 1918). These authors showed a dasyclad with central stem-cell bearing whorls of thin hair-like sterile branches below, and fused calcified cuplike fertile whorls above, each fertile whorl partially embracing the next: the plant is completed by a tuft of hair-like branches forming the terminal umbel, calcified at the base to give a perforate, “pepper-pot top”, structure. The Morellets worked on loose, dissociated, elements from the unconsolidated sediments of the Paris Basin, and besides typical fertile whorls they had calcified evidence of the sterile portion of the plant, of the lower, atypical fertile whorls, of the terminal structure, and of the serial association of the fertile whorl.

Remarks: *Clypeina jurassica* is a common microfossil in the Upper Jurassic of southern and central Europe, North Africa and the Middle East, and records of it are material from Switzerland, and re-described for comparison with Clypeina inopinata (Favre 1932), the next advance was the description of Algerian material by Morellet (1951) based on both thin-section and solid (silicified) specimens.

The descriptions drawn up for this species by Favre, Morellet and Donze all differ slightly in detail. The principal difference is that speciments from the type-area (Switzerland) show a lower maximum number of sporangial tubules per vertical that do those from some other localities. For Swiss material Favre gives a relevant count of 10-17, and Donze 7-17, whereas Morellet, with Algerian examples, gives 11-20, and the Middle East material (above), shows up to 24 (Elliott, 1968).

Stratigraphic range & distribution: Upper Jurassic, Circum-Mediterranean and Middle East.

Salpingoporella Pia, 1918

(Plate 18, figures 2-6; Plate 19, figures 1-4)

<u>Phylum</u>: Chlorophyta

<u>Family</u>: Dasycladaceae

<u>Tribe</u>: Diploporeae

<u>Sub-Tribe</u>: Salpingoporellinae

Genius: *Salpingoporella*

Type species: *Salpingoporella muelhbergii* (LORENZ 1902) PIA *in* TRAUTH 1917

1953 *Salpingoporella annulata* Carozzi: 384, figs.1-55.

1955b *Salpingoporella annulata* Carozzi: Elliott: 125-126.

1955a *Salpingoporella annulata* Carozzi: Carozzi: 55, pl.6, figs.5-7, text-fig.15.

1960 *Salpingoporella annulata* Carozzi: Elliott: 221.

Diagnosis: small, rod-like, thick-walled, calcified, tubular dasyclad, with regular successive verticals of relatively few simple single branches which widen to the exterior and open as simple pores: thallus not segmented, but interverticil portions sometimes outwardly slightly convex and delimited by grooves.

Description (based on Carozzi): small, tubular, calcified dasyclad, straight or slightly curved and usually occurring in fragments of up to 1mm. Or more in length, external diameter 0.30-0.64 mm., internal diameter 0.10-0.25mm. apart, each vertical consisting of 8-12 simple straight radial branches which widen terminally and open in a shallow external horizontal annular groove. Pores alternate in position form one vertical to t4he next, and between them the external interverticil walls are gently convex.

Remarks: the Qatar material corresponds with Carozzi's type material in detailed morphology, number of branches per vertical, etc.: the maximum size seen (external diameter 0.60) is a little less than Carozzi records, and the minimum measurement encountered for this dimension (0.26 mm.) is also less than that given for the type-material. Since the closely similar *S. apenninica* Sartoni and Crescenti differs mostly in its smaller size, a series of Qatar specimens were carefully measured for outer and inner diameter and spacing between verticils. Of thirteen such examples, only one fell completely within the limits given for the smaller species, and it is considered that this is best regarded as a small example of *S. annulata.* At Qatar the material consists of short lengths only of tube, occurring amongst ooliths and rounded fragments and often rolled, and it may be that sorting has occurred before burial (Elliott, 1968).

Stratigraphic range & distribution:

Upper Jurassic-bottom Cretaceous (Kimmeridgian, Portlandian-Valanginian) of Switzerland and Southern France, Italy, Jugoslavia : and of Middle East (Arabia); Qatar, Trucial Oman and Hadhramaut

4.1.3.2. Thaumatoporellacean Algae (calcareous red algae)

Thaumatoporella parvovesiculifera Raineri, 1922

(Plate 19, figures 5-6; Plate 20, figures 1-6)

Phylum: Rhodophyta

Family: Thaumatoporellalean

Genius: *Thaumatoporella*

Morphologic Features:

cm-size although crustose forms can reach decimeter size. It has several growth habits: a) as fragments of encrusting , nodular and rigid, branching plants, b) as erect, articulated, branching or arborescent forms, c) as massive encrusters and binders, and d) as coatings on other grains (forming rhodoids or rhodoliths).

Fragile, branching forms are found in moderate wave energy areas. Encrusting, nodular, and robust branching forms can withstand very high wave energy. Indeed, red algal encrusters are the dominant binding organisms in most Cenozoic to modern reefs.

T. parvovesiculifera Raineri, 1922 is present within the upper part of the Jubaila Formation and lower part of Arab Formation where it is almost consistently developed. It is typically found above the massive stromatoporoid biofacies, and in the presence of the branched stromatoporoid *Cladocoropsis mirabilis*, together with foraminifera such as *Kurnubia palastiniesis*, *Nautiloculina oolithica*, *Mangashtia vienotti, Pfenderina salernitana, Trocholina alpina* and undifferentiated miliolid foraminifera. It displays an encrusting habit, and tubular forms may have encrusted some vegetative material that has not been fossilized.

Stratigraphic range & distribution**:** Triassic –Late Cretaceous

4.1.4. STROMATOPOROIDS

A Polyphyletic group of calcified demosponges and calcareans. They possess a primary skeleton of spicules around which is precipitated a secondary calcareous skeleton often composed of fibrous calcite.

Stromatoporoids are quite large fossils, typically several centimeters in diameter, with occasional giant specimens of up 30 cm or more. Identification to species level is, however, based on micro-scale features such as wall structure and type and orientation of spicules (Wood, 1987). Thus, stromatoporoids qualify as microfossils despite their large size. the significance of the micro-based taxonomy is that identification to species level is generally possible based on thumb-nail sized samples (e.g. plugs). Stromatoporoids are thus potentially useful in sub-surface stratigraphic studies, particularly in high-energy grain supported facies where other microfossil groups such as calcareous algae are commonly absent.

Stromatoporoids occur prolifically at certain levels in the Upper Jurassic of the Tethyan realm, notably in the Middle East, where stromatoporoid build-ups form important hydrocarbon reservoir units up to 5 m thick, e.g. in Arab D reservoir of Ghawar and Khurais (de Matos, Kawaguchi, 1991; Mitchell *et al.,*1988).

Stromatoporoids that occur in our study (the upper part of the Jubaila Formation and lower part of Arab Formation in subsurface) are all allochthonus stromatoporoids that include the branched species *Cladocoropsis mirabilis* together with stratified forms which fall under *Burgundia* sp.species. Both of these two species could refer to *Burgundia* genus. In outcrops we found another species of the stromatoporoid *Shuqraia* sp. which is similar to Cladocoropsis in morphology which is always branched or dendroid.

Burgundia Dehorne, 1916

(Plate 21, figures 5-6; plate 22, figures 1-5)

Phylum: Porifera

Class: Demospongiae

Subclass: Ceractinomorpha

Family: Burgundidae

Genius: *Burgundia*

Type species: *Burgundia trinorchii* Dehorne, 1916. Vers (Saone et Loite), France.Upper Jurassic (Portlandian).

1901 *Burgundia trinorchii* Munier-Chalmas (1883); Tornquist, p.1116 (nomen nudum).

1909 *Burgundia trinorchii* Munier-Chalmas (1883); Haug, p. 931(nomen nudum).

1917 *Circoporella hayasaka*,p. 57.

1920 *Burgundia semiclathrata* (Hayasaka,1917); Dehorne, p.73.

1930 *Plassenia* Yabe and Sugiyama, p. 113.

1054 *Bekhmeia* Hudson,p. 48.

Diagnosis: Aspiculate calcified demosponges with an ability to produce perforated concentric laminae, as well as tabulae. Fibrous microstructure of the calcareous skeleton, ranging from orthogonal to fascicular fibrous. Massive, nodular, or dendroid gross morphology. Aquiferous units may possess tabulate oscula and/or astrorhizae.

Stratigraphic range & distribution:

Europe, USSR, Japan, Upper Jurassic to Lower Cretaceous (Upper Oxfordian-Hauterivian).

Shuqraia Hudson, 1954

Phylum: Porifera

Class: Demospongiae

Subclass: Tetractinomorpha

Order: Axinellida

Family: Milleporellidae

Genius: *Shuqraia*

Type species: *Milleporidium zuffardi* Wells, 1943. Mount Aiya Makkeran, Harrar Province, Ethiopia , Somalia), Japan? Upper Jurassic (Upper Oxfordian-Lower Kimmeridgian).

1935 *Milleporidium somaliense* Zuffardi-Comerci, 1932; Thomas, pp.37-38, pl.5

1954 *Shuqraia zuffardi* (Wells, 1943), Hudson, p.218, pl.7

1954 *Shuqraia heybrocki* Hudson, pp. 214-215, pl.6.

1955 *Shuqraia Zuffardi* (Wells, 1943); Hudson,pp. 237-238,pl.23, figs.2 (T.S).

1966 *Shuqraia heybrocki* Hudson, 1954; Turnsek, pp.80-81, pl. 7 and 8 (T.S).

Diagnosis: Milleporellidae with a primary spicule framework of styles (max.80 µm long, 7µm wide) in a loosely packed, plumose arrangement. Dendroid gross morphology. Calcareous skeleton of regular columns forming tubules (140 µm in diameter) parallel to branch axis, then normal to it. These appear as a vermiculate mesh in tangential section. Orthogonal to fascicular fibrous primary calcareous skeleton in which the pillar diameter is 80-130µm. thin aligned tabulae (5-20m thick) form in the younger central area of the skeleton. Secondary epitaxial calcareous skeleton (up to 50 m thick) and fibrous aligned tabulae (up to 130 m thick) often present in mature areas of the individual. this is often concentrically zoned. Pillars are shorter in the mature outer areas. tabulae often with periodicity to define latilaminae. No mamelons. May or may not posses astrorhizae.

Remarks: spicules have only been found in *Shuqraia hethira* (Hudson, invalid name; synonymized here with *S. zuffardi*) and in specimens collected by the present author. Because of similarity of the construction of the calcareous skeletons, a similar speculation is inferred for other specimens allocated to this genus.

Hudson described the fibrous tabulae (filling tissue), as transverse or coenosteal lamellae, or concentric laminae. These laminae are merely aligned and periodically precipitated tabulae which form concentric bands, and are not laminae as recognixed and defined in this work. Since these aligned fibrous tabulae are generally found in the older outer parts of the skeleton, Hudson described the skeleton as having an axial and peripheral reticulum.

In Hudson's (1954b) original description of *Shuqraia*, he allocated it to the family Stromatoporinidae. The type genus of this family, *Stromatoporina*, was redescribed by Hudson (1955a), and he felt that *Shuqraia* could no longer be included in the family. In 1956, he placed *Shuqraia* in the Milleporiidae, because of the presence of ancestral 'zooidal tubes' (Dehorne) or 'autotubes' (Hudson). The new-found speculation indicates that it is a member of the Milleporellidae, within the order Axinellida.

Stratigraphic range & distribution:

Middle East (south Arabia, south Israel), North Africa (Ethiopia, Somalia), Japan?. Upper Jurassic (Upper Oxfordian-Lower Kimmeridgian).

4.1.5. BRYOZOANS

Bryozoans

(Plate 23, figure 6; Plate 24, figure 1)

Phylum: Bryozoa

Class:Gymnolaemata

Order: Cheilostomida

Morphologic Features:

Bryozoans are colonial, polyp-like, lopophorate invertebrate animals that are distinquished by their U-shape digestive track. Entoproct bryozoans have an anal opening inside their circle of tentacles; ectoproct bryozoans are characterized by having an anal opening outside or below the tentacles. Each xooid inhabits a hardened exoskeleton (zooecium) and forms encrusting thread-like or sheet-like, massive, nodular, hemispherical, ramose, bifoliate, fenestrate, or tuft-like colonies.

The main differences between bryozoans and corals are the typically smaller size of bryozoan colonies and individual living chambers, and the outward thickening of bryozoan living chamber (zooecial) walls. Unlike red algae or corals, bryozoans have acanthorods and mesopores.

Stratigraphic range& Distribution: Middle Cambrian-Recent; cosmopolitan.

4.1.6. CALCAREOUS NANNOPLANKTON

Nannofossils are small marine organisms (1-100µ in size) and divided into two main groups which include coccoliths and nannofossil spicules. Our section of the upper Jubaila and the lower Arab formations are dominated by didemnid ascidian spicules, derived from benthic marine organisms commonly called sea squirts (tend to be facies susceptible).Coccoliths, which are important in our study because they are derived from marine planktonic organisms (not facies controlled).Only three coccolith genera exist in Upper Jubaila and Lower Arab Formations and many ascidian spicules. We only used the coccoliths where present, but where the coccolith taxa are absent in the studied section we used ascidian spicules only for correlation purposes. The calcareous Nannoplanktonic Taxonomy of this thesis was provided by Dr. O. Varol, Varol Research, UK.

Phylum: Haptophyta

Class: Coccolithophyceae

4.1.6.1. *Didemnoides* Bonet & Benveniste-Velasquez, 1971

Type species**:** *Didemnoides rosetta* Bonet & Benveniste-Velasquez, 1971

Remarks: Asteroid spicule made up of 10 to 24 rays. The tips of the rays are usually in triangular shape. The species of this genus is distinguished by the width of the rays**.**

Didemnoides radiatus Varol, n. sp.

(Plate 34, figure 1)

Diagnosis**:** Species of *Didemnoides* having 10 to 24 slender rays. The maximum width of spicule rays is less than 2.5µm.

Derivation of name**:** Latin for "rayed" referring to its multi rays.

Holotype: Pl.3, Fig. 31

Type level: Jubaila Formation

Type locality**:** Diplomat Field Samples, near Riyadh

Dimension of holotype**:** Diameter = 16.0µm.

Remarks: This asteroid spicule is made up of 10 to 24 rays. The spicule appears brownish-blue under polarised light. The tips of the rays are triangular in shape. The maximum width of spicule rays is less than 2.5µm.

Stratigraphic range& Distribution:

Late Jurassic. The last occurrence of this form was noted in the upper part of the Jubaila Formation.

Didemnoides rosetta Bonet & Benveniste-Velasquez, 1971

(Plate 33, figure 3)

1971 *Didemnoides minutum* Bonet & Benveniste-Velasquez, p.10-11, pl. 2, figs. 1-6, pl. 3, figs. 1-6.

Remarks**:** The species of *Didemnoides* is made up of 10 to 24 rays. The maximum width of spicule rays is always greater than 2.5µm. The tips of the spicule rays are triangular in shape. *Didemnoides rosetta* is distinguished from *Didemnoides radiatus* and *Didemnoides multiradiatus* by having wider spicule rays (maximum width is not less than 2.5µm).

Stratigraphic range& Distribution:

Late Jurassic. The last occurrence of *Didemnoides rosetta* was noted in the upper part of Arab D Formation.

4.1.6.2. *Velasquezia* Varol, n. gen.

Type species: *Uniplanarius praegothica* Herrle, 2002.

Diagnosis: Didemnid ascidian spicules made up of four fusiform rays.

Derivation of name: In honour of N. Benveniste-Velasquez, Instituto Mexicano Del Petroleo, Mexico.

Remarks: The joined part of the rays is usually shorter than the free part of the rays. The spicule rays are identical in size in well preserved species. *Velasquezia* differs from *Acinodidemnum* by having four rays whereas the latter have a single ray and two bilateral appendices. The spicules classified in *Velasquezia* are similar to species of *Uniplanarius* but differ from it by having a single cycle. Moreover, species of *Velasquezia* under polarised light when gypsum plate is inserted display opposite colour distribution to that of species of *Uniplanarius.*

Velasquezia minuta (Bonet & Benveniste-Velasquez) Varol, n. comb.

(Plate 36, figure 6)

1971 *Didemnoides minutum* Bonet & Beneviste-Velasquez, p. 11-13, pl.1, figs.3-4, 7, 11, 12, non pl.1 figs. 1-2, 6, 9, 10, 14-19.

Remarks: In this spicule **f**our fusiform rays are joined to form an asymmetrical cross. The opposite angles of the cross are equal. The free parts of the rays are usually greater than the joined part of the rays.

Stratigraphic range& Distribution: Late Jurassic -Pleistocene.

Velasquezia praegothica (Herrle) Varol, n. comb.

(Plate 37, figure 3)

1971 *Didemnoides minutum* Bonet & Benveniste-Velasquez, pl.1, figs. 9, 12, non pl. figs. 1-8, 10-11, 13-19.

2002 *Uniplanarius praegothica* Herrle, p. 78, pl. 6, fig. 23.

Remarks: The spicule is made up of 4 fusiform rays. The spicule rays are joined to each other at right angle. *Velasquezia praegothica* is distinguished from *Velasquezia minutum* by the arrangement of rays. In *Velasquezia praegothica* rays join each other at right angle to form an axial cross. In *Velasquezia minutum* spicule rays join each other to make asymmetrical cross in which opposite angles are equal.

Stratigraphic range& Distribution: Late Jurassic - Pleistocene.

4.1.6.3. *Cyclagelosphaera* Noel, 1965

Type species**:** *Cyclagelosphaera margerelii* Noel, 1965

Cyclagelosphaera omanica Varol, n. sp.

(Plate 35, figure 5)

Diagnosis: A large species of *Cyclagelosphaera* (10-13µm) with 24 to 36 elements.

*Derivation of name***:** After Oman where this form was first recovered.

Holotype: Pl.2, Fig. 1

Type level**:** Jubaila Formation

Type locality**:** Diplomat Field Samples, near Riyadh

Dimension of holotype**:** Diameter = 12.0µm.

Description: This large circular form has a small central are surrounded by a narrow tube cycle. The shields are monocyclic and birefringent under polarised light. Maximum size of *Cyclagelosphaera omanica* ranges between 10 and 13µm. The number of elements on the shields varies between 24 and 36.

Remarks: *C. omanica* is distinguished from *Cyclagelosphaera deflandrei* by its smaller size. The latter has maximum size not less than 13µm and not recorded above the early Oxfordian Hanifa Formation in Arabian Peninsula. The poorly preserved specimens of *Cyclagelosphaera omanica* may be confused with the ascidian spicule *Didemnoides radiatus. Cyclagelosphaera omanica* always appear brownish to yellowish whereas *Didemnoides radiatus* always appears brownish-blue under polarised light. Moreover, *C. omanica* has a distinct central area and a tube cycle whereas *D. radiatus* lacks these features.

Stratigraphic range & distribution:

Late Jurassic. The last occurrence of this form was noted at the top of the Jubaila Formation.

4.1. 7. ACCESSORY FOSSILS

A varied assemblage of accessory fossil material is recorded from Arab D reservoir carbonates. Macrofossil debris derived from fragmentary echinoid and bivalve material represents the single most common component encountered. Within this category, the usually very finely fragmented echinoid debris observed represents quantitatively the dominant fraction; in the more unfossiliferous sections, it is often the only biogenic material present.

There are lesser amounts of small agglutinated foraminifera such as chrysalindinid, *Verneuilina minuta, Praechrysalindina* spp. and *Siphovalvulina* spp. Larger specimens may be further identifiable as *cf. Iraqia and cf. Satorina* Other forms include occasional *Haplophragmoides* spp.. *Ammobaculites* sp., *Ammodiscus* sp., Bigenerina sp., *Kilianina* sp. and *Biloculinella*.

Other components are represented by the occurrence of moderately common to rare microgastropods, ostracod shell material and the microproblematicum *Aeolisaccus*, whilst coporolithic material more distinctive than ordinary pellets includes *Prethocoprolithus centripetalus*, codiacian algae (*Lithocodium aggregatum* Elliot, 1956, *Cayeuxia piae* Frollo and *Rivularia piae*), dasycladacean algae (*Cylindroporella Arabica* Elliot 1957), together with pelecypods, bryozoa, echinoid debris and sponge spines and solitary corals.

The very rare occurrences of the cyanophyte alga are recoreded within the Arab D reservoir and poor preservation makes the identification of this taxon tentative in studied wells.

4.2. PALAEOENVIRONMENT

In this chapter, a general and robust picture of the palaeoenvironmental indicators of the Jubaila and Arab biocomponents is presented from literature. It is imperative to have a detailed understanding of environment of deposition for any given biofacies which are being studied in chapters five and six. The succession of microfossil associations recognized within the Upper Jubaila and Lower Arab Formations are mainly indirectly related to palaeo-water depths. The associations appear to be more directly linked to energy levels within the depositional system are not to be linked to chronostratigraphic restriction. In general, these will be broadly linked to palaeo-water depths.

4.2.1. BENTHONIC FORAMINIFERA

Palaeoecological distributions of foraminifera in the carbonate environments have a wider coverage and include Henson, 1950; Reulet, 1982; Saint-Marc, 1982; Jordan *et al.*, 1985; Banner and Whittaker,1991; Alsharhan and Nairn, 1986 and Banner *et al.*,1991. Certain fossil larger benthic foraminifera probably harboured photosynthetic algal symbionts. As such, might be expected to have exhibited the same kind of zonation (by symbiont type) as modern counterparts (Cowen, 1983 and Whittaker *et al*., 1998).

The foraminiferal distributors documented by Banner & Simmons (1994) are regarded as accurate as they are calibrated against algal distributions (determined by depth at which photosynthesis can occur). Using such foraminiferal and algal distribution data from closely spaced core samples from Jubaila and Arab Formations, it was possible to draw palaeobathymetric curves that effectively describe eustatic sea-level and hence, their primary control by depositional facies.

Banner & Whittaker (1991) in their review of some of the Middle Eastern Cyclamminidae showed that the size of the alveoles in the hyperdermis can be related to the environment in which the foraminifer lived and consequently to the lithofacies and biofacies in which the particular taxa are found. Thus *Alveosepta* sp., *Everticyclammina* sp. and *Pseudocyclammina* (with very narrow hypodermal alveoles), appear to have inhabited deeper water (15-80m) or to have tolerated water rich in argillaceous suspensions; both of which would cause reduced illumination. In contrast, the foraminifera have large alveoles and are found in clear limestone, often associated with dasyclad and codiacean algae. They appear to characterize shallow, inner neritic (5-20m) environment, where the seawater was of very low turbidity (Whittaker *et al*., 1998).

At the very base of the studied succession in the upper Jubaila Formation, where low numbers of smaller calcareous benthonic foraminifera were found, a more directly depth-related association can be proposed. In the relatively shallow marine carbonate successions of the Jurassic, such forms, especially *Lenticulina* spp. and *Nodosaria* spp., appear to range no shallower than mid inner neritic (perhaps around 20 m water depth).

This is probably related to competition, substrate and feeding strategy, with the miliolid and smaller agglutinated foraminifera being more successful in colonizing the shallower depositional settings (Banner and Simmons, 1994).

With slight upwards shallowing, but still relatively low to only moderate energy levels, mud-rich deposits probably contain both epifaunal and infaunal microfossil elements. The example is *Kurnubia palastiniensis* most typically infaunal (living at least partly within the uppermost sediment layer) and the thin-shelled ostracods my be most typically epifaunal (living on or above the sediment surface). Such associations may imply water depths from about 20 m up towards 15 m, or even 10 m. (Aillud, *et a*l., 2002).

With further slight shallowing there is a relative increase in grain content and the chlorophyte alga *Thaumatoporella parvovesiculifera* appears often in abundance. Water depths of around 10m for the initiation of this association can be postulated, supported by reported depth of penetration of red-orange light in sea water, this being the primary absortion peak of chlorophytes (Banner and Simmons, 1994). It can be suggested that the initial consolidation of the soft substrate afforded by *Thaumatoporella Parvovesiculifera* permitted secondary solonisation by an epifaunal foraminiferal assemblage, such as the often abundant miliolid and smaller agglutinated forms. These may usually have been excluded from inhabiting such a palaeoenvironment by lack of a sufficiently stable substrate. The distribution of the foraminifera may effectively be dependent upon the alga for colonization. These sections are often observed to contain a microfossil assemblage rich in fragmentary bioclastic debris derived from larger benthonic organisms that were not dependent upon substrate consolidation for successful colonization.

From 10m to 5m the association of shallowing, algal colonization and the establishment of an epifaunal microfossil assemblage where dasycladean algae predominate, the substrate stabilizing effect may have been partly related to their rhizomes (roots). The result would, however, have been similar, with the provision of a partly sheltered setting where smaller foraminifera could become established, despite at least moderate energy levels and rather coarse grained sediments.

At around 5 m water depth, average wave and current energy levels became too great for the algae to maintain their widespread position within the palaeoenvironmental setting such as costal waters and outer shelf. In contrast, the *stromatoporoid* and *Cladocoropsis* flourished in the latter environment. In coastal waters, the absence of the algae may remove the shelter necessary for the smaller foraminifera to thrive and larger foraminifera flourished such as *Pfenderina* sp, *Trocholina* sp. and *Quinqueloculina* dominate.

4.2.2. DASYCLADACEAN ALGAE

They occur in warm shallow coastal waters in sheltered situations in tropical and subtropical seas, and in areas marginal to the latter, such as the Mediterranean. Their maximum abundance is said to be from low-tide level to 5m depth, extending down in diminishing abundance to 10m., althoug there are scattered occurrences below this to 30 m, depending on intensity of illumination and clearness of water.

The sheltered parts of coastal bays and some lagoons are favoured habitats, and they are tolerant of the reduced salinities which may occure there. Probably, like most nonstenohaline marine organisms, they are euryhaline and have a limited tolerance for temporary conditions of increased salinity (Elliott, 1968).

The Upper Jurassic of Middle East (Kimmeridgian-Tithonian) yields a florule of *Clypeina jurassica*, *Salpingoporella annulata* and *Cylindroporella arabica* occur in fine-grained and oolitic limestones associated are numerous crustacean coproliths, *Favreina salevensis,* and small gastropods and foraminifera. The picture is again of shallow, clear limy bottomed waters, possibly lagoonal or enclosed (Elliott, 1968).

4.2.3. THAUMATOPORELLACEAN ALGEA

The palaeoenvironment of the alga *Thaumatoporella parvovesiculifera* appears in water depths of around 10 m for the initiation of this “red algae” to be dominant. This is supported by the reported depth of penetration of red-orange light in sea water the primary peaks of the photobioactivity spectrum for chlorophytes (approximately 675 millimicrons), supplemented by secondary peaks (approximately 450 millimicrons) in the 0-10m depths of costal waters (0-15m) of outer shelf, less turbid waters) but only the secondary photobioactivity peaks can be used by the algae in greater depths reducing chlorophyte productivity (Banner and Simmons, 1994).

In a detailed analysis of the habitat and mode of growth of *T. parvovesiculifera*, Elliott (1979) has shown that this algae was primarily an epigenous form which was able to grow on unconsolidated carbonate substrates. Growth in such a depositional setting consolidated the soft sediment and through this, significantly increased substrate stability. It can be suggested that the initial consolidation of the soft substrate afforded by *T.*

parvovesiculifera permitted secondary colonization by an epifaunal foraminiferal assemblage (Aillud *et al*., 2002).

Thaumatoporella parvovesiculifera is present within the upper part of the Jubaila Formation and the lower part of the Arab Formation where it is almost consistently developed. It is typically found above the massive stromatoporoid facies, and in the presence of the branched stromatoporoid *Cladocoropsis mirabilis*, together with foraminifera such as *Kurnubia palastiniesis, Nautliloculina oolithica, Mangashtia vienotti, Pfenderina salernitana, Trocholina alpina* and undifferentiated miliolid foraminifera. It displays an encrusting habit, and tubular forms may have encrusted some vegetative material that has not been fossilized (Hughes, 2005).

4.2.4. STROMATOPOROIDS

Late Mesozoic stromatoporoids had strict ecological requirements and consequently they are sensitive palaeoenvironmental indicators. They appear to have been gregarious and are largely confined to mid-upper shoreface facies in highstand systems tracts where they form biostormes and bioherms up to 5m thick. Stromatoporoids appear to have been strictly stenohaline, and are normally associated with diverse open marine biotas which include brachiopods, corals, bryozoa and echinoids. Stromatoporoids are notably absent from high salinity facies such as the Arab C, B and A of central and eastern Arabia.

Palaeowater depths for abundant in situ specimens of stromatoporoids are estimated at less than 10m based on the position of life assemblages in vertical shoaling-up sequences.

Despite their limited morphological variability, Late Mesozoic stromatoporoids appear to have occupied a number of ecological niches, Turnsek *et al*.(1981), in a detailed study of an Upper Jurassic platform-margin ‘reef complex’ in Slovenia, identified three environmentally-significant stromatoporoid-coral faunas:

١. An actinostomariid fauna representing an outer barrier reef zone; characteristic genera include *Astrostylopsis*, *Actinostromina, Coenstela, Sporadoporidium, Tubuliella, Sphaeractinella, Ellipsactinina* and *Cylicopsis*.

٢. A parastomatoporoid fauna representing an inner barrier reef zone; this zone is dominated by *Parastromatopora,* with subsidiary *Dehornella*, *Hudsonella*, *Reticlina* and *Shuqraia.*

٣. A *Cladocoropsis* fauna representing a back reef lagoon; this area is dominated by *Cladocorpsis mirabilis* Felix, 1906.

Equivalents of the parastromatoporoid and *Cladocoropsis* faunas can be found in Saudi Arabia Upper Jurassic, though the astinostromariid fauna is evidently not represented, perhaps because of environmental constraints and/or provincialism (Simmons, 1994).

4.2.5. CALCAREOUS NANNOFOSSILS

The nannofossil species which carried out in this study to assist and enhance our palaeobathymetric interpretations. The calcareous nannofossils helped to recognize the palaeoenvironment of Upper Jurassic Formations by finding the occurrence of open marine taxa (coccoliths). Coccolths are good indicators whether the environment was deep (consistence appearance in the section) or maximum flooding events (if it pulses in the section).

CHAPTER FIVE

BIOFACIES AND THEIR PALAEOENVIRONMENTS

5.1. BIOFACIES

5.1.1. INTRODUCTION

A biofacies is a facies that is characterized by a particular assemblage of fossils. The carbonates of the upper Jubaila Formation and Arab D member of Arab Formation contain moderately high diversity of species, of which benthonic foraminifera are typically dominant, but bivalve, echinoid, calcareous algae and stomatoporoid debris are also well represented. *Kurnubia palastiniensis* and *Nautiloculina oolithica*, echinoid and bivalve debris persist throughout both the Jubaila and Arab Formations, and are therefore of limited in palaeobathymetric and correlation values. Stratigraphic distribution of the non-persistent species defines nine major bio-assemblages, which permit the designation of nine biofacies (Figure 5.1).

A variety of microfaunal, microfloral and fragments of macrofaunal and macrofloral elements exist within each study localities. Appendices B (Figures 1-3) illustrate the vertical distribution of selected forms within localities and these events have been used to identify nine biofacies as illustrated in Figure 5.2.

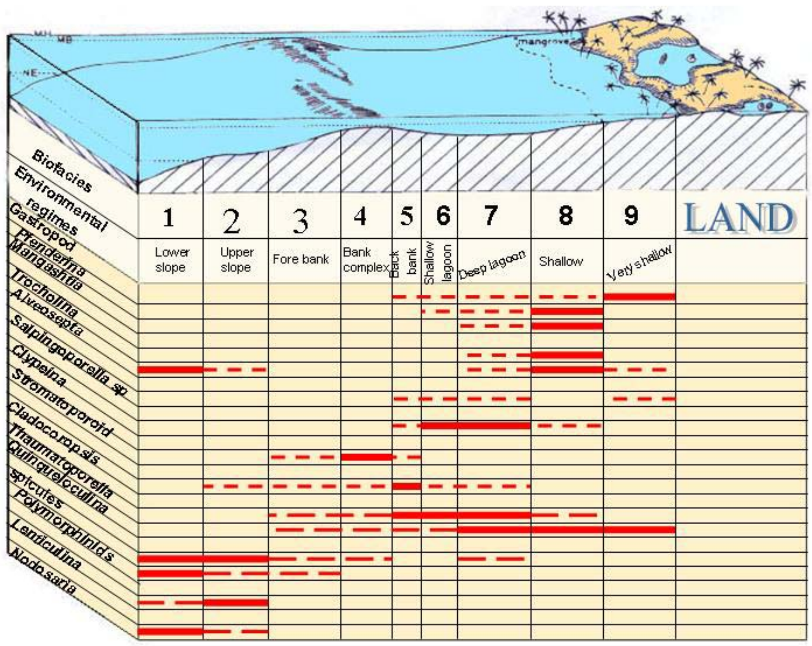

Figure 5.1. Model for the palaeoenvironmental distribution of various biocomponents within the upper Jubaila and Arab Formations.

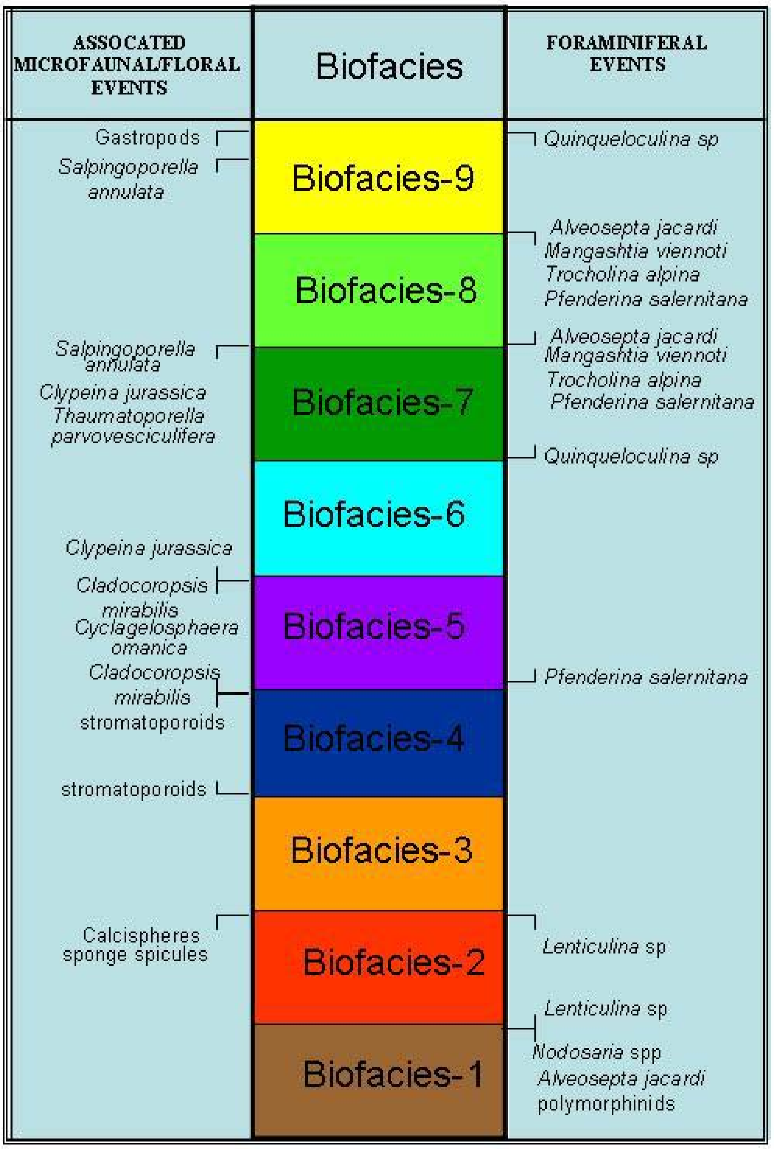

Figure 5.2. Microfaunal/floral and foraminiferal events for every biofacies of upper Jubaila and lower Arab Formations

5.1.2. BIOFACIES SIMILARITY AND DIFFERENCES AMONG THE OTHER STUDIES

The biofacies and their associated palaeoenvironments in this study can be compared with the carbonate facies of Wilson (1975), but they do not correspond one-to-one. Wilson's facies 2 (open shelf) is equivalent to biofacies 1 (deep upper slope), 2 (upper slope) and 3 (fore bank) of this study; biofacies 4 (bank crest) is equivalent to Wilson's facies 5 (organic reef); Wilson's facies 6 (sands on edge of platform) is equivalent to biofacies 5 (back bank); Wilson's facies 7 (open platform) is equivalent to biofacies 6 (distal shallow lagoon), 7 (deep lagoon) and 8 (proximal shallow lagoon) and Wilson's facies 8 (restricted platform) is equivalent to biofacies 9 (very shallow environment) (Table 5.1).

TABLE 5.1. A comparison between Wilson's carbonates facies and biofacies, established in this study.

Wilson's facies (1975)	**Biofacies (this study)**
2 (Open shelf)	1,2 and 3
5 (Organic reef)	4
6 (Sands on edge of platform)	5
7 (Open platform)	6,7 and 8
8 (Restricted platform)	9

The first recognition of vertical organisation of various microbiocomponents and palaeoenvironmental interpretation of the Jubaila and Arab formations was by Hughes (1996) where he defined 18 bioevents and three biofacies D1, D2 and D3 in descending stratigraphic order in Ain Dar, Shedgum and Uthmaniyah areas. Biofacies D3 is restricted to deep marine which approximates with the Jubaila Formation. Biofacies D2 and D1 are within the Arab D carbonates. Dhubeeb (2001) studied the Arab D reservoir in the Hawyaih area and established five biofacies two in the Jubaila and three in the Arab D member, that were later supplemented by Dhubeeb (2002a), Dhubeeb (2002b), Hughes and Dhubeeb (2002) and Hughes (2004).

5.1.3. THE UPPER JUBAILA AND LOWER ARAB BIOFACIES

In this thesis, the use of the Arab D reservoir samples in eight fields and Jubaila and Arab Formations exposures enable refinement of the upper Jubaila and lower Arab Formations into nine biofacies. Biofacies 1 and 2 are restricted to the open marine, normal salinity, moderately deep marine conditions, below normal fair-weather wave base (25-30m?). These biofacies are characterized by the presence of *Lenticulina spp.*, *Nodosaria spp*., sponge spicules and *Alveosepta jacardi*. Biofacies 3, 4 and 5 are typified by the shoal complex that includes both laminated and branched stromatoporoids, of which the laminated form is interpreted as being typical of the distal, higher energy regime of the shoal, probably above wave base. The branched stromatoporoid *Cladocoropsis mirabilis* is typically found stratigraphically above the laminated form, and concluded to have prograded out from the lagoonal shoal flank, near wave base.

These five biofacies have been confirmed to lie in the Jubaila Formation, of which biofacies 5 is possibly coincident with the top of the Jubaila Formation.

The other four biofacies are within the Arab D carbonates. The Arab D carbonates are restricted to a lagonal regime which ranges from deep lagoon, normal salinity setting to a hypersaline, very shallow lagoon to intertidal environment. The deepest biofacies of the Arab D member is represented by the presence of the dasyclad algae *Clypeina jurassica* and the encrusting algae *Thaumatoporella parvovesciculifera*. A slightly shallower lagoon subtidal setting includes *Pfenderina salernitana, Mangashtia viennoti, Trocholina alpine* and miliolids. A hypersaline, shallow lagoon to intertidal environment is characterized by presence of miliolids, cerithid gastropods, large bivalve and brachiopod debris and algal laminae.

Nine major palaeoenvironmental units have been interpreted based upon the various downhole appearances and disappearances of biocomponents in this study.

Biofacies 1 (deep upper slope) (upper Jubaila Formation)

The upper Jubaila Formation in outcrop sections and the lower section of the Arab-D reservoir in subsurface samples is simply characterized by the constant presence of monaxon and tetraxon sponge spicules, agglutinated foraminifera *Alveosepta jacardi, Nodosaria* spp. and indeterminate polymorphinids with FDA of sporadic presence of calcareous foraminifera *Lenticulina* sp.

Biofacies 2 (upper slope) (upper Jubaila Formation)

Defined by first downhole appearance (FDA) of *Alveosepta jacardi* and *Nodosaria* spp. and inconsistent rare occurrences of polymorphinids, monaxon and tetraxon sponge spicules. Locally presence of fragments of allochthonous *Cladocoropsis mirabilis* and that is attributed to storm-triggered transportation from a shallower setting.

The biofacies 1 and 2 were deposited under low energy, normal salinity conditions below storm wave base and considered to represent in situ deeper marine forms which would suggest relatively deeper conditions with a less restricted environment than that in the overlying section.

Biofacies 3 (fore bank) (upper Jubaila Formation)

The deeper marine benthonic foraminiferal species that characterize biofacies 1 and 2 of the underlying mud-dominated section are absent within biofacies 3 and defined as poor fossiliferous section with inconsistent rare occurrences of *Thaumatoporella parvovesciculifera* and as well as sponge spicules.

Species that maintain a constant presence within this biofacies include *Kurnubia palastinienses*, *Nautiloculina oolithica*, echinoid and bivalve debris, scattered stromatoporoids and *Cladocoropsis mirabilis*, and miliolids and *Textularia* spp. foraminifera which are considered to be allochthonuos shallower marine forms that were contemporaneously transported into the environment. Large bivalves, miliolids and *Cladocoropsis* fragments are locally present at levels that seem to coincide with packstones, and form the lower parts of upwards grading, mudstones-dominated cycles that are considered to be storm-generated distal turbidities (Meyer and Price, 1993).

Biofacies 4 (bank crest) (upper Jubaila Formation)

This biofacies is defined by the absence of *Clypeina jurassica* (below the last downhole presence of *Clypeina jurassica*) and the constant presence of stromatoporoid fragments with sporadic presence of sponge spicules (monaxon and tetraxon) which continue through this biofacies to approximate the top of this biofacies. It also has inconsistent rare occurrences of *Cladocoropsis mirabilis, Thaumatoporella paravesiculifera* and *Quinqueloculina sp.*.

Biofacies 5 (back bank) (top of Jubaila Formation)

It is defined by the first downhole occurrence (FDA) of stromatoporoids and consistent rare to common of *Cladocoropsis mirabilis.* The rare, but consistent presence of *Thaumatoporella paravesiculifera* and the sporadic presence of *Clypeina jurassica, Quinqueloculina sp.* and gastropods.

The top of this biofacies is coincident with the top of Jubaila Formation, as defined in chapter six in this study and coincides approximately with a nannofossil time line defined by Varol (2000).

Forebank, bankcrest and backbank are assigned in the shoal complex regimes for biofacies 3,4 and 5 respectively. They also typified by oolitic grains and packstone-grainstone lithological texture.

Biofacies 6 (distal shallow lagoon) (Arab D member)

This biozone is defined by the rare to common constant presence of the calcareous alga *Clypeina jurassica* and *Thaumatoporella paravesiculifera* and abundant to common *Quinqueloculina sp.* These biocomponents are much reduced at the base of the biofacies. In addition, this biofacies is characteriseed by the inconsistent and rare occurances of *Cladocoropsis mirabilis, Pfenderina salernitana, Salpingoporella annulata* and gastropods.

Biofacies 7 (deep lagoon) (Arab D member)

This biofacies is defined by the constant common to rare occurrence of *Clypeina jurassica,* the continued presence of abundant to common *Quinqueloculina sp.* and *Salpingoporella annulata,* continued rare occurances of *Thaumatoporella paravesiculifera,* and the base of rare to present of *Trocholina alpina*, *Mangashtia viennoti* and *Alveosepta jacardi.* This biofacies is the deepest biofacies of the Arab D member and the relatively high species diversity is interpreted as suggesting normal salinity conditions.

Biofacies 8 (proximal shallow lagoon) (Arab D member)

This biozone is characterized by a variety of biocomponents which would suggest a very shallow marine environment. Biofacies 8 contains the persistence of certain species which were present in underlying biofacies, and include *Kurnubia palastinienses, Nautiloculina oolithica*, echinoid and bivalve debris and miliolids It is characterized by the consistent presence of *Trocholina alpina*, *Mangashtia viennoti*, *Pfenderina* *salernitana* and *Alveosepta jacardi*. Packstone/grainstone predominate and suggest moderately high energy conditions, and water depths within the effects of wave base.

Biofacies 9 (very shallow environment) (Arab D member)

A hypersaline, very shallow lagoon to intertidal environment is characterized by the presence of miliolids, cerithid gastropods, large bivalve and brachiopod debris and algal laminae. This biofacies is the uppermost part prior to the deposition of the anhydrites, and is typically depleted of foraminifera.

<u>5.1.4 Regional Biofacies Distribution</u>

<u>Biofacies 1</u>

Biofacies 1 tends to best develop towards KHRS well which has the thickest section of this biofacies where the intrashelf basin biofacies is best represented. During the depositional of this biofacies paleohighs are interpreted for the ANDR and ABSF wells where this biofacies is not developed.

<u>Biofacies 2</u>

This biofacies is best developed in FZRN and DQ which have thickest part of biofacies 2 but it becomes thinner towards the south of HWYH well and QTIF wells. This could suggest that the area from FZRN to DQ may lie within an intrashelf basin and KHRS well has this biofacies but was possibly affected by little local highs which could not provide enough accommodation space. Biofacies 2 is not developed in ANDR and ABSF because they represent localized paleohigh settings.

Biofacies 3

This biofacies is developed in local are as in north Ghawar including ANDR, SDGM and HWYH as well as the DQ section. The presence of this biofacies in these wells may suggest that the stromatoporoids complex just started to develop at this time or that their localities were close to the shelf margin.

Biofacies 4

Biofacies 4 is dominated by stromatoporoid fragments and developed only in central Ghawar field in UTMN and HWYH wells as well as all outcrops localities.

Biofacies 5

Biofacies 5 is considered in this study at the top of Jubaila Formation. It is developed in most of the studied localities except QTIF, FZRN and KHRS wells which are still too deep to be colonized by the *Cladocoropsis mirabilis* biofacies.

Biofacies 6 and 7

Biofacies 6 and 7 are typical of a shallow environment particularly lagoonal, except in FZRN well and outcrop localities which are occupied by very shallow biofacies. This suggests that FZRN well may have represented a local high at the time of deposition of this biofacies or the sea level dropped too rapidly to allow the *Clypeina* *jurassica* to flourish. The Helwah and Okla sections are interpreted to be similarly too shallow to develop *Clypeina jurassica* at this time.

Biofacies 8 and 9

These biofacies occur in all studied localities except in ABSF which has no core samples in the upper part of Arab D reservoir, and also in the DQ section where the beds that may have contained this biofacies have been removed by erosion, as they are typically platy soft beds (easy to be eroded).

The first three biofacies are best developed in DQ but this does not mean that the palaeoenvironment of DQ is much deeper than the others, but it means that only this locality has sampled the lower parts of the Jubaila Formation. It also worth stating that the open marine environment representing biofacies 1 and 2 and coccoliths were only found at the DQ section and not in other outcrop localities. This similarly does not mean that this environment did not exist at other outcrop localities, but is considered to be due to the availability of Jubaila samples only in DQ section as the other outcrops only sampled the uppermost part of the Jubaila Formation.

5.2. BIOFACIES PALAEOENVIRONMENT

5.2.1 THE REGIONAL DEPOSITIONAL ENVIRONMENT INTERPRETATIONS

A series of biofacies maps were generated to display the palaeoenvironment variations from upper Jubaila Formation to the top of the Arab D member.

During deposition of the open marine biofacies (Biofacies 1, 2 and 3) which characterized the lower upper Jubaila Formation, the stromatoporoid shoals prograded possibly from the southeastern Saudi Arabia towards the intrashelf basin in the north (Figure 5.3).

Figure 5.4 shows the widely distributed area of stromatoproid banks, from ABSF well in the east to the Jubaila outcrops in central Saudi Arabia.

Figure 5.5 displays the palaeoenvironment of studied locations at the Jubaila-Arab boundary which are characterized by the predominance of the *Cladocoropsis* biofacies (Biofacies 5) in most of studied localities except three wells, QTIF, FZRN and ANDR wells which are located within deep marine settings associated with an intrashelf basin.

The Arab Formation biofacies are displayed in Figures 5,6 and 5.7, and indicate the shallow environment setting associated with the Arab D outcrops as well as in north Ghawar field in FZRN well.

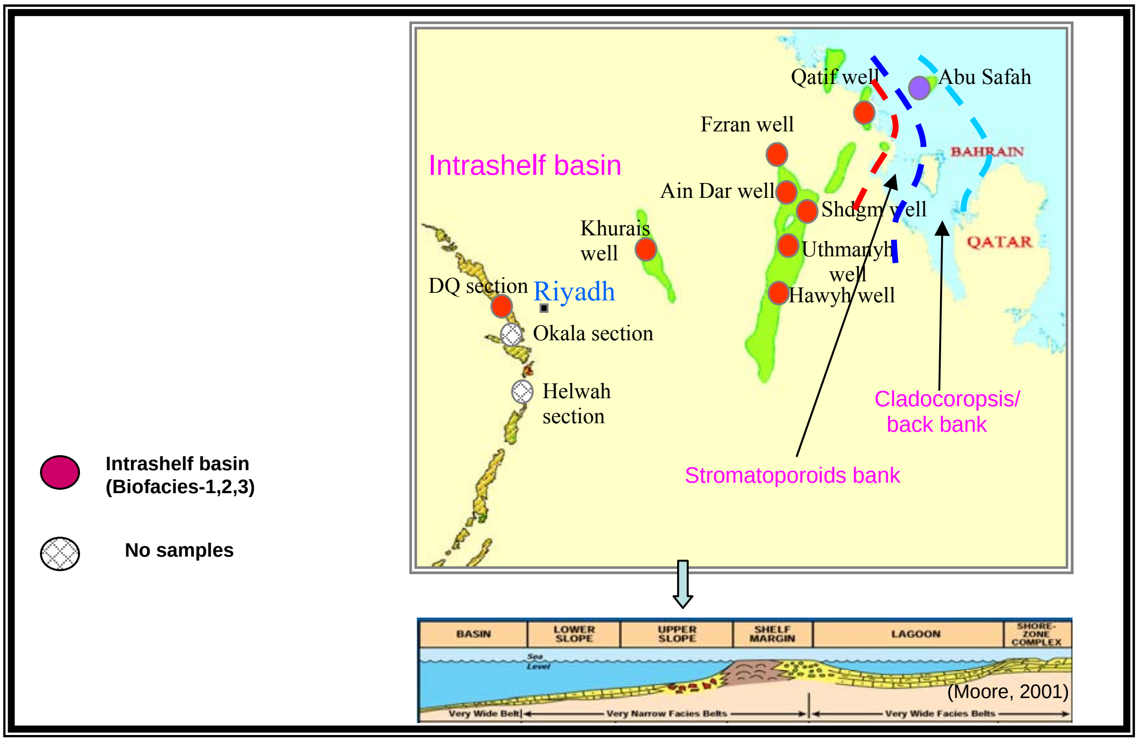

Figure 5.3. Map showing palaeoenvironment variation for deeper biofacies of Jubaila Formation (biofacies 1, 2 and 3).

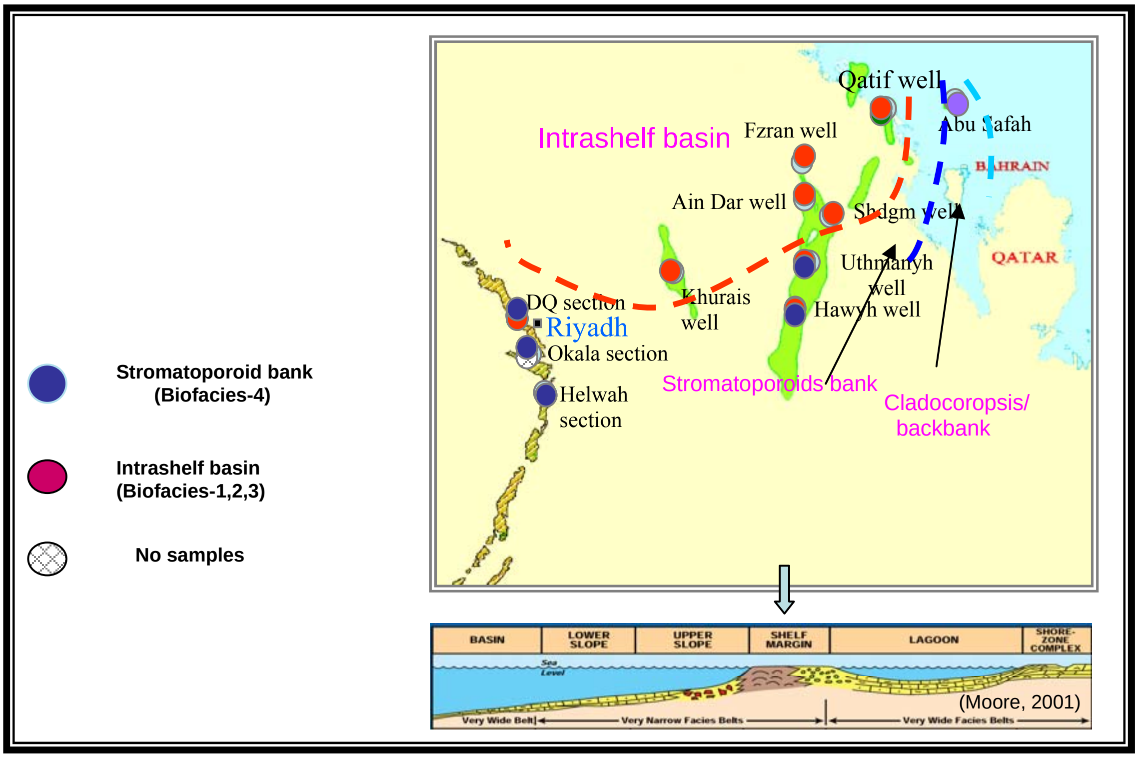

Figure 5.4. Map showing palaeoenvironment variation during the deposition of biofacies 4.

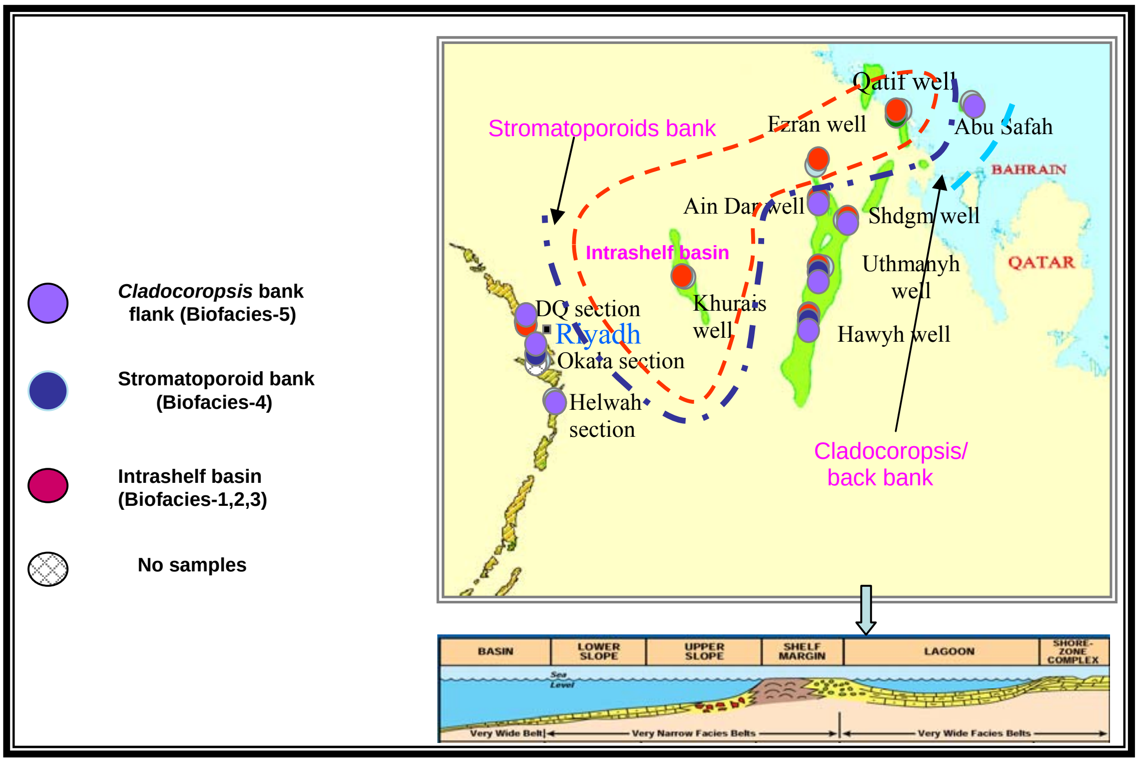

Figure 5.5. Map showing the palaeoenvironment of top biofacies-5 which characterized the Jubaila-Arab Formational contact (biofacies 5)

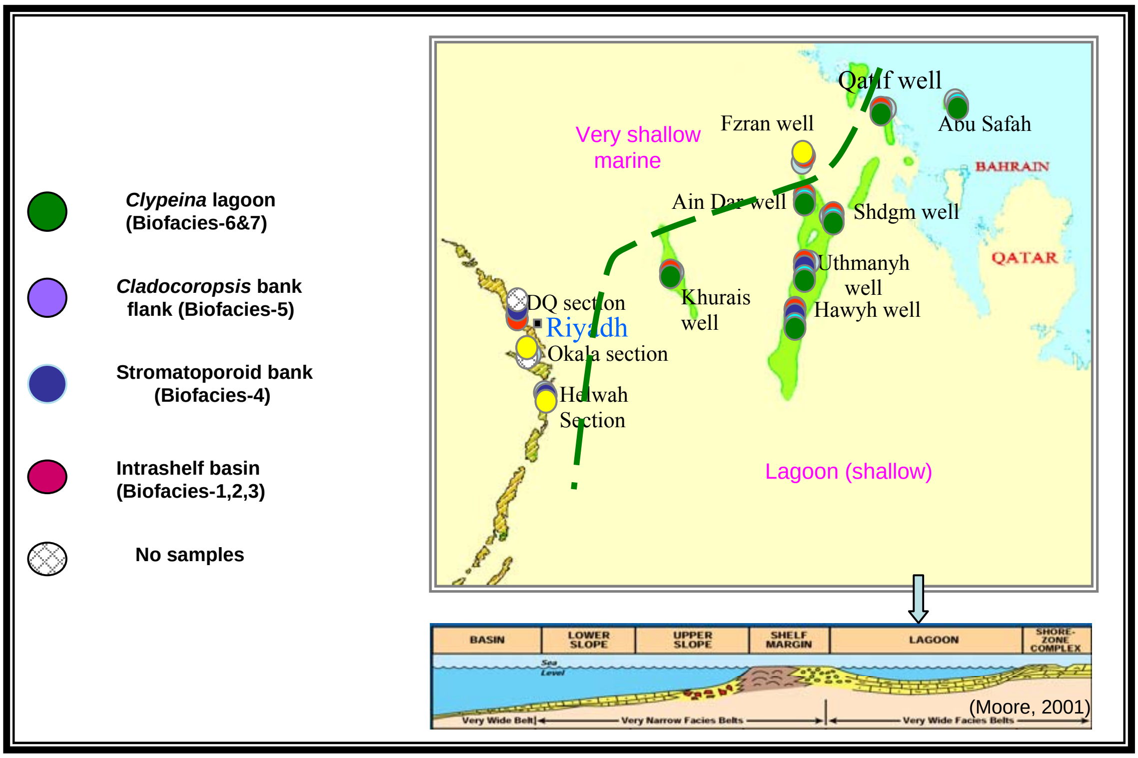

Figure 5.6. Map showing palaeoenvironment variation of lower Arab D member (biofacies 6 and 7).

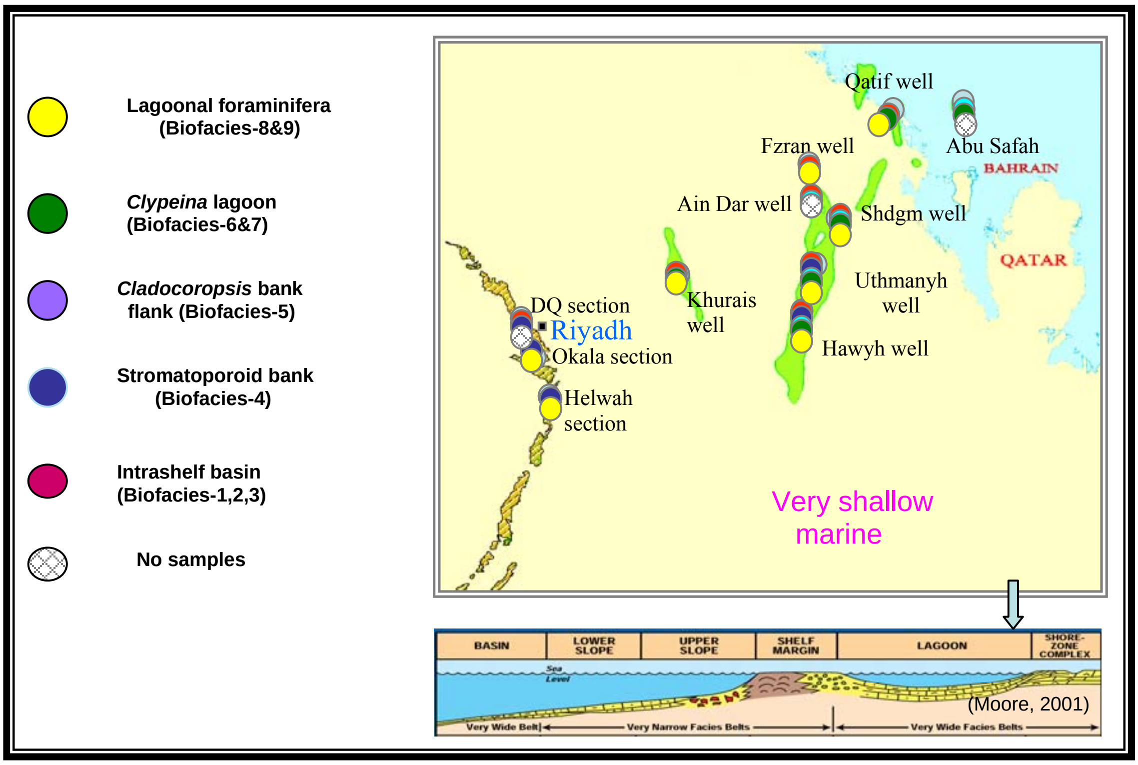

Figure 5.7. Map showing palaeoenvironment variation during the deposition of shallow marine biofacies (biofacies 8 and 9).

CHAPTER SIX

RECOGNITION OF THE JUBAILA AND ARAB FORMATIONAL CONTACT

6.1. INTRODUCTION

The Jubaila-Arab formational boundary was defined based on Jubaila and Arab exposures in Riyadh area (but this boundary has not been characterized in the subsurface). Recent studies in Arab Formation outcrops (Meyer et al., 1996 and Le Nindre and Vaslet, oral communication 2002 and 2004, (see Appendix C)) characterized the Jubaila top by the last stratigraphic occurrences of the stromatoporoid fragments, these being the domed/ encrusting types.

6.2. RECOGNITION OF THE JUBAILA AND ARAB FORMATIONAL CONTACT FROM BIOFACIES

The nine biofacies of this thesis provide a high resolution vertical distribution fauna and flora variations of the upper Jubaila and lower Arab Formations through that boundary. This data gives some evidence that the candidate boundary should be at the top of the *Cladocoropsis* biofacies (branched stromatoporoid).

These evidences are listed below:

a. Although the presence of Cladocoropsis is noted in the upper Jubaila, but it associated with rare to common stromatoporoid fragments which their occurrences limited only in the upper most the Jubaila Formation in three outcrop sections. This could suggest that the Cladocoropsis biofacies excited in outcrops and can use them as the Jubaila top indicator but it was not well develop and that could be at stage of beginning growth before the very shallow environment sediments deposited.

b.The presence of coccoliths particularly *Cyclagelosphaera omanica,* consistently to the top of DQ section supports that *Cladocoropsis* biofacies is in open marine regime not in restricted lagoon and it dose so in subsurface samples. It also supports that the Cladocoropsis biofacies appeared in the top of open Jubaila marine (if we assume that the end top of this section is the Jubaila top) (Figure 6.1).

c. In Okla and Helwah sections, the biofacies 8 which characterized by shallow biocomponent such as Trocholina alpina, Pfenderina salarenitana and Alveosepta jacardi with abundance influx of quartz grains immediate overlain the predominated stromatoporoid biofacies with rare *Cladocoropsis* biofacies which suggested that the Cladocoropsis biofacies can not tolerate in the lagonal and tidal depositions which dominated the lower Arab Formation (Figure 6.2).

d. The biofacies 8 and 9 are characterized the Arab D member in outcrop sections and the Arab Formation is defined base on these sections, so the *Cladocoropsis* biofacies can not be part of Arab Formation.

e. The *Cladocoropsis* and *Clypeina* biofacies are the most wide distribution in studies localities and the only *Cladocoropsis* biofacies occurred in both outcrops and subsurface localities which makes this biofacies is very important for correlate the exposures in the central Arabia to the wells in the east whereas the stromatoporoid biofacies is limited mostly in outcrop localities.

These evidences provide good findings of how define the top of Jubaila Formation by:

١. The constant presence of *Cladocoropsis mirabilis* (Biofacies 5) (Figure 6.1).

٢. The constant absence of the lagonal dasyclad Clypeina *jurassica* (Biofacies 6).

٣. The continued occurrence of nannoplankton coccoliths, although their FDA is sometimes misleading due to storm derived events. In UTMN and SDGM wells, rare occurrences of coccoliths have been noted in very shallow environment. Below reservoir Zone 2B, however, their constant influx starts, here considered as a good marker for the top of the Jubaila. The coccoliths as explained in Chapter 2 of this thesis, play a significant role as not only do they provide evidence for the deep sitting but also are useful for correlation since their lateral continuity is autochthonous and represents the time line event at the top of the Jubaila Formation.

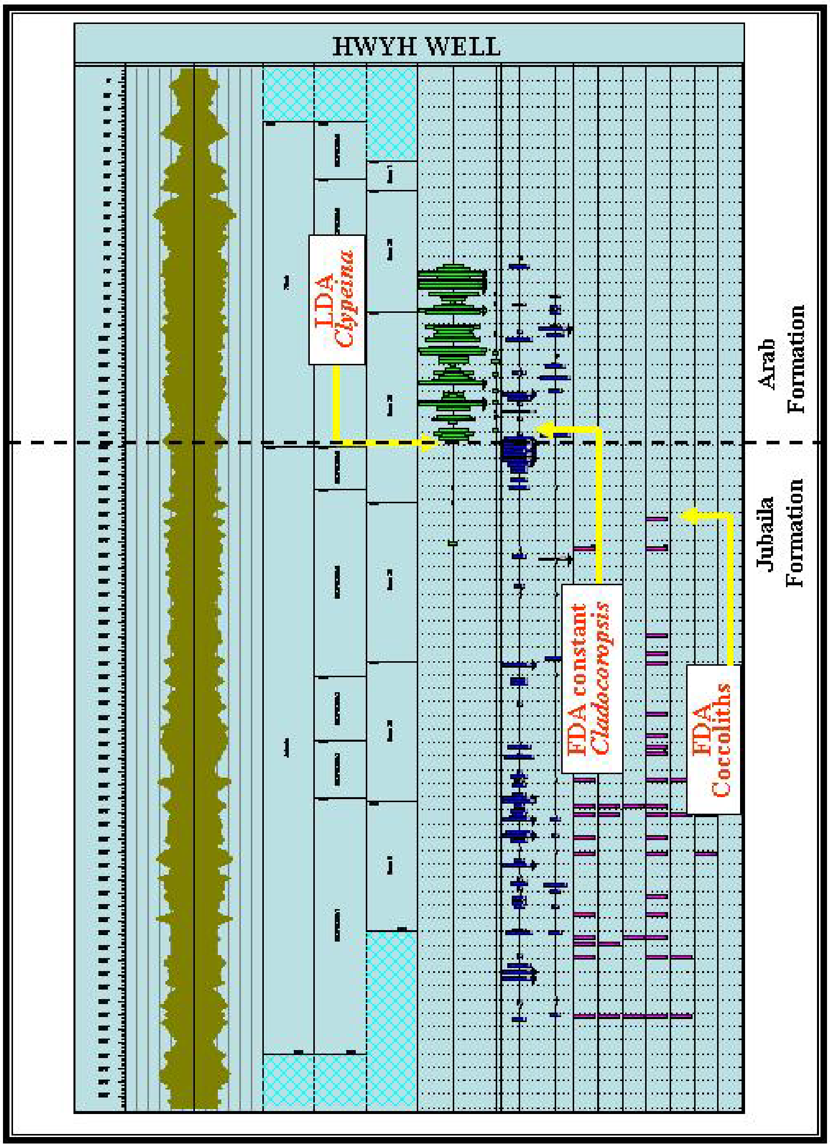

Figure 6.1. Transition change from biofacies 5 to biofacies 6 where there is no missing biofacies at the Jubaila-Arab contact in HWYH well.

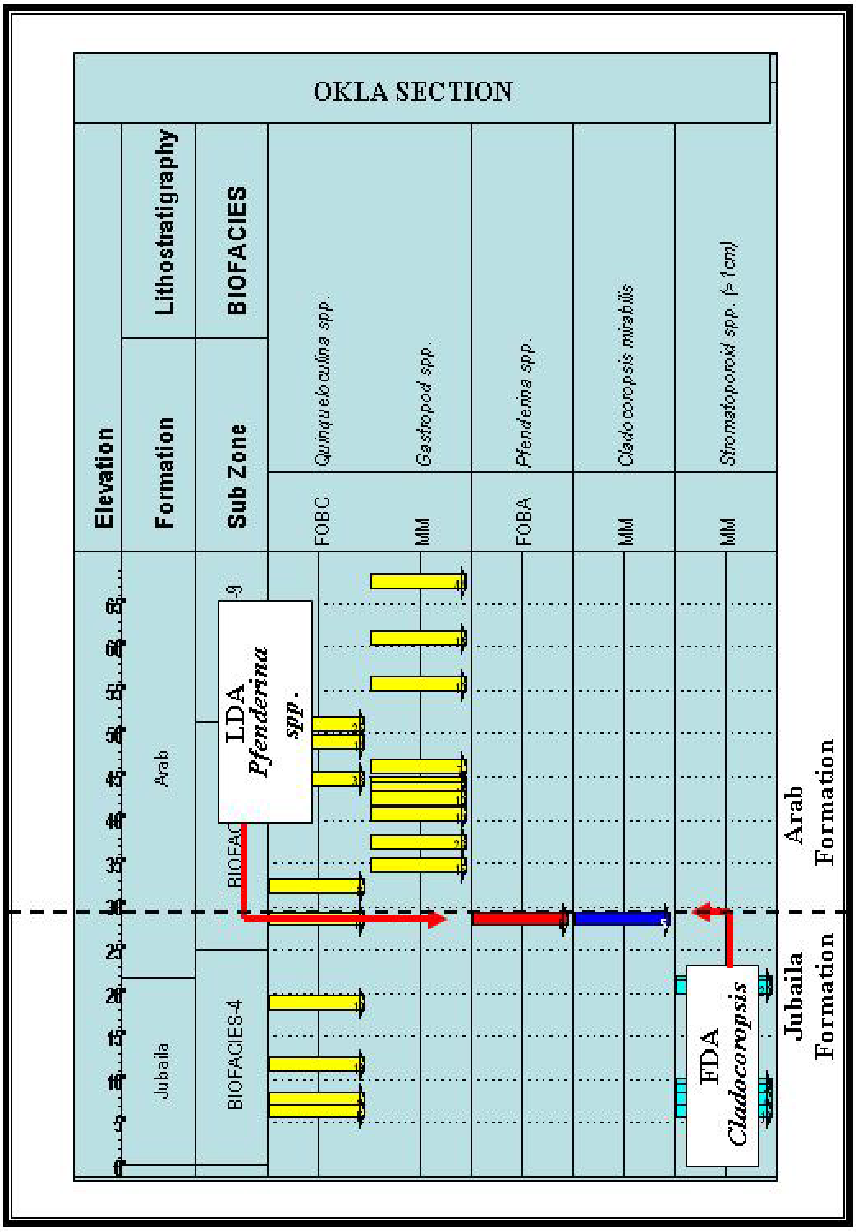

Figure 6.2. Biofacies 8 overlaying the biofacies 5 where the Jubaila-Arab contact in Okla Section in Wadi Nissah.

6.3. RECOGNITION OF THE JUBAILA-ARAB CONTACT FROM WIRELINE LOGS

The Jubaila-Arab contact is located below the first increase of the gamma ray (GR) log below reservoir zone 2B in Ghawar field and reservoir 2 in KHRS field (Enclosures 3-8).

In QTIF well, this event is picked a few feet above reservoir zone 2B. We need to see samples beneath this interval to make sure that the last downhole occurrence (LDA) of *Clypeina jurassica* is not local and may continue to below 2B. In this well, the Arab D cores did not go deeper into the Arab D reservoir zone. In this well the GR does not help to recognize the possible contact (Enclosures 2).

In ABSF, the Jubaila-Arab contact coincides with the first reduction of GR downhole. It appeared in reservoir zone 4, which is much earlier than in other wells (Enclosures 1).

QTIF and ABSF wells need a review of the current reservoir top picks currently in the Aramco database and use the new ones that the reservoir characterization currently use, as this would then place the event with similar characteristics as in Ghawar field, where the Jubaila-Arab contact is considered to possibly represent a time line.

The Jubaila-Arab contact is easy to pick it from GR once the nature of the biofacies contact has been determined. In ABSF well, or example, the contact is represented by Biofacies 7 that directly overlies Biofacies 5, with the expected

intervening Biofacies 6 not represented and this palaeoenvironmental event coincides with a change in GR logs. A similar situation is present in the FZRN well where

Biofacies 8 directly overlies Biofacies 2 (Enclosures 7). In the HWYH well, however, this boundary is less easy to identify, where Biofacies 6 overlies Biofacies 5, and coincides with a transition zone of changing environment and is difficult to pick it by using the GR log alone (Enclosures 4).

The difference between the abrupt or transitional biofacies and palaeoenvironmental contact can be demonstrated not only by GR as explained above, but also by using other wireline logs such as porosity logs; such data is not available for restriction set by Saudi Aramco.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

The upper Jubaila Formation shows the last large scale highstand system track of mega Jurassic system cycle and from upper Jubaila to Arab Formation are representing one cycle of system track from highstand in upper Jubaila to late highstand in Arab D member.

New biofacies scheme for the upper Jubaila Formation and Arab D member**.** Nine biofacies have been defined, including: (1) Lower slope; (2) Upper slope; (3) Fore bank; (4) Bank crest; (5) Back bank; (6) Distal shallow lagoon; (7) Deep lagoon; (8) Proximal shallow environment and (9) Very shallow lagoon.

This study looked for biofacies fingerprints of the Jubaila and Arab formations to accurately identify the Arab D member and Upper Jubaila Formation contact regionally. Accurate identification of this boundary has proved to be of considerable importance for it divides the reservoir into two parts each with a decidedly different biofacies characters.

This study provides confirmed that the top of Jubaila is characterized by the presence of predominant Cladocoropsis biofacies, not by the presence of stromatoporoids as previous studies considered.

This study generates new palaeoenvironment maps of the upper Jubaila Formation and Arab D member and this may assist locating new Jubaila top.

The biofacies of this thesis show subparallellism to reservoir zones which increase our knowledge of the relationship between the reservoir zones and the stratigraphic units (top Jubaila Formation).

The variety of these biofacies provides valuable independently gained events for lateral correlation and a unique contribution for palaeodepositional environmental reconstruction. Their integration with sedimentological, petrographic and wireline logs provides a significantly improve efforts to develop depositional and reservoir-facies models within fields as well as regional.

The distribution of primary porosity is mostly dependent upon the depositional energy regime, and the biofacies can provide such basic information.

7.2. RECOMMENDATIONS

١. Use the Jubaila-Arab contact as datum to hang a correlation panel instead of at the top of the Arab D reservoir.

٢. Use quantitative micropalaeontological analysis particularly in biofacies 4, 5 and 6 to give confident compartmentalization of the Jubaila and Arab Formations.

٣. Use the new reservoir zonation picks in each field instead of existing ones or at least need to correct top Jubaila "pick" in the "tops" database

٤. Use nannofossil data to assist the interpretation of depositional environments.

٥. Use the HWYH well in any further study because it is one of the ideal wells in this study that has the following:

- Complete cores recovery from top Arab D reservoir to the base.
- The only one of this study that has complete 9 biofacies.
- The only one that using quantitative micropalaeontology analysis and the others with semi-quantitative manner.
- The only one has FDA of coccoliths and FDA influx of coccoliths at same depth with top of biofacies 5 (Jubaila-Arab contact).
- Has the dolomite intervals lesser in thickness than others in this study.

6. Study thin sections side by side with core descriptions and measured sections of outcrops to see the distribution of macrofossils through the sections such as coral, *Cladocoropsis* and stromatoporoid fragments which easy to miss them during the processes of sampling the sections or plugging the cores (usually

avoid taking sample with only one fragment of stromatoporoid or coral, particularly the outcrop sections).

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PLATES

THIN SECTION PHOTOMICROGRAPHS

PLATE 1

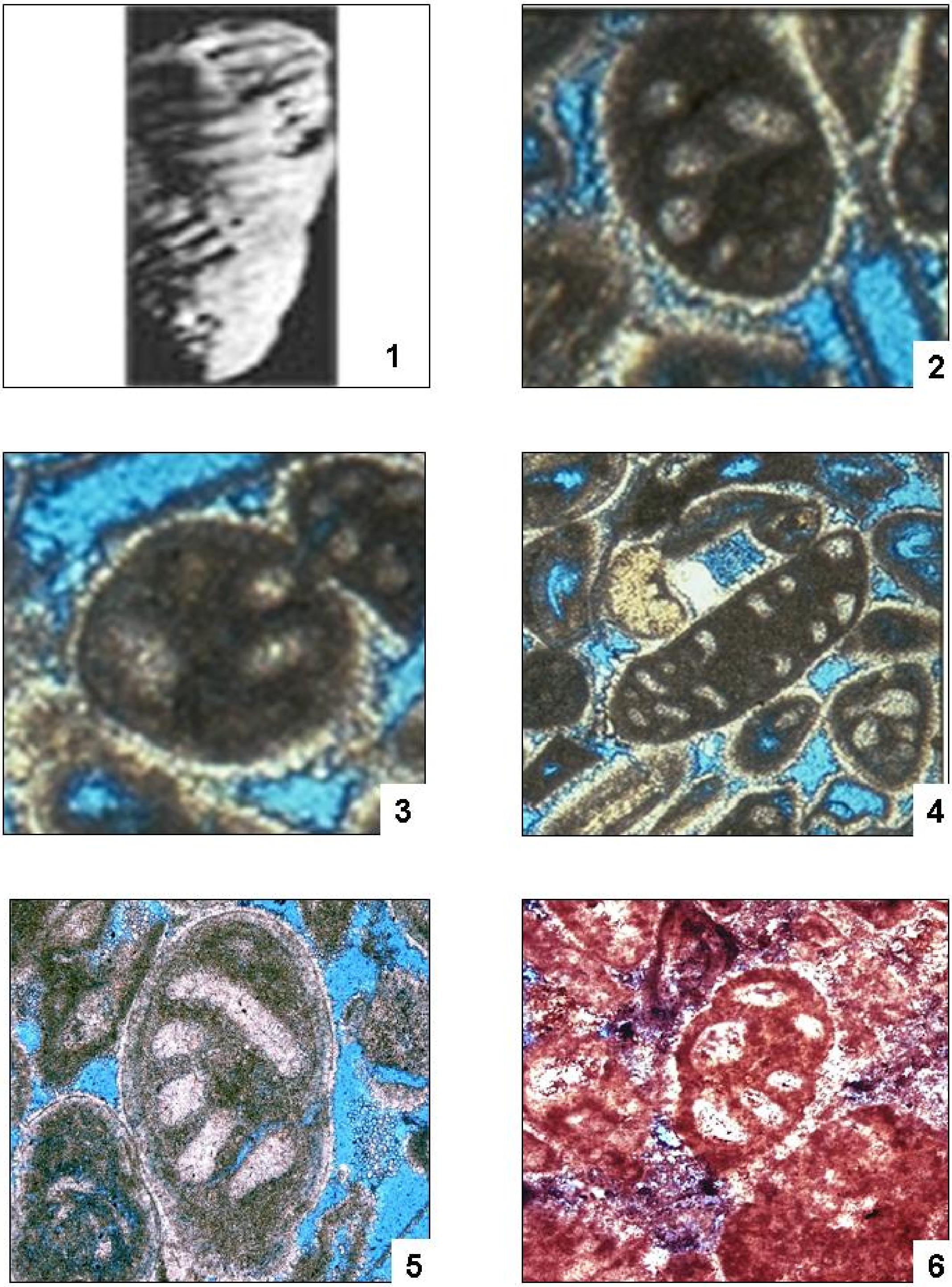

PLATE 1

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Pfenderina salernitana* Henson, 1948, lateral view.(5X)

Figure 2. Photomicrograph of *Pfenderina salernitana*, subaxial vertical section, KHRS. (5X)

Figure 3. Photomicrograph of *Pfenderina salernitana*, transverse section, HWYH well. (5X)

Figure 4. Photomicrograph of *Pfenderina salernitana*, vertical axial section, HWYH well. (5X)

Figure 5. Photomicrograph of *Pfenderina salernitana*, oblique transverse, QTIF well. (5X)

Figure 6. Photomicrograph of *Pfenderina salernitana*, oblique transverse section, KHRS well. (5X)

PLATE 2

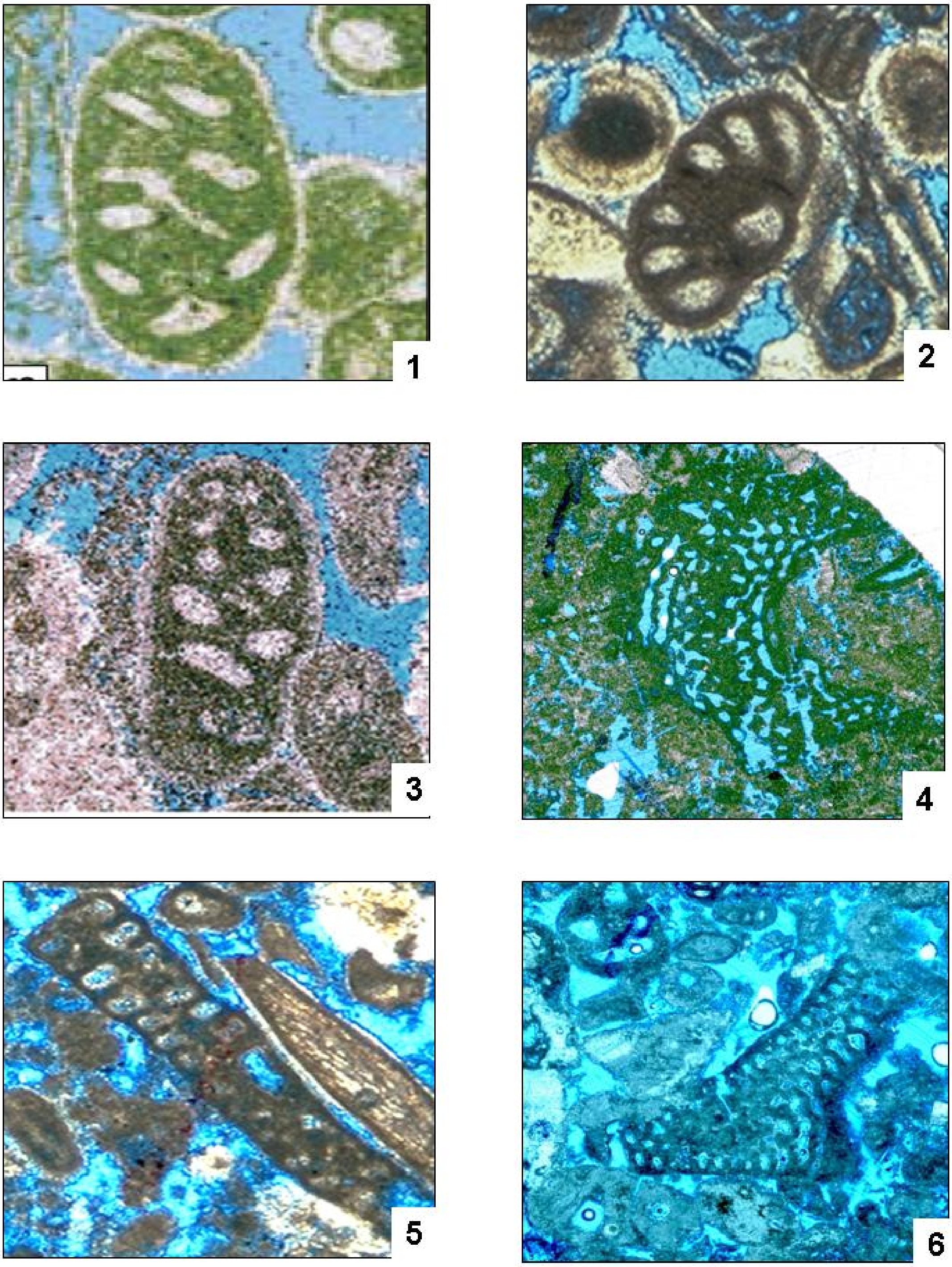

PLATE 2

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Pfenderina salernitana*, oblique vertical section, ABSF well. (5X)

Figure 2. Photomicrograph of *Pfenderina salernitana*, transverse section, HWYH well.(5X))

Figure 3. Photomicrograph of *Pfenderina salernitana*, oblique vertical axial section, ABSF well. (5X)

Figure 4. Photomicrograph of *Mangashtia viennoti*, tangential vertical section, ANDR well. (1.6X)

Figure 5. Photomicrograph of *Mangashtia viennoti*, axial vertical section, HWYH well. (5X)

Figure 6. Photomicrograph of *Mangashtia viennoti*, subaxial vertical section, SDGM well**. (5X)**

PLATE 3

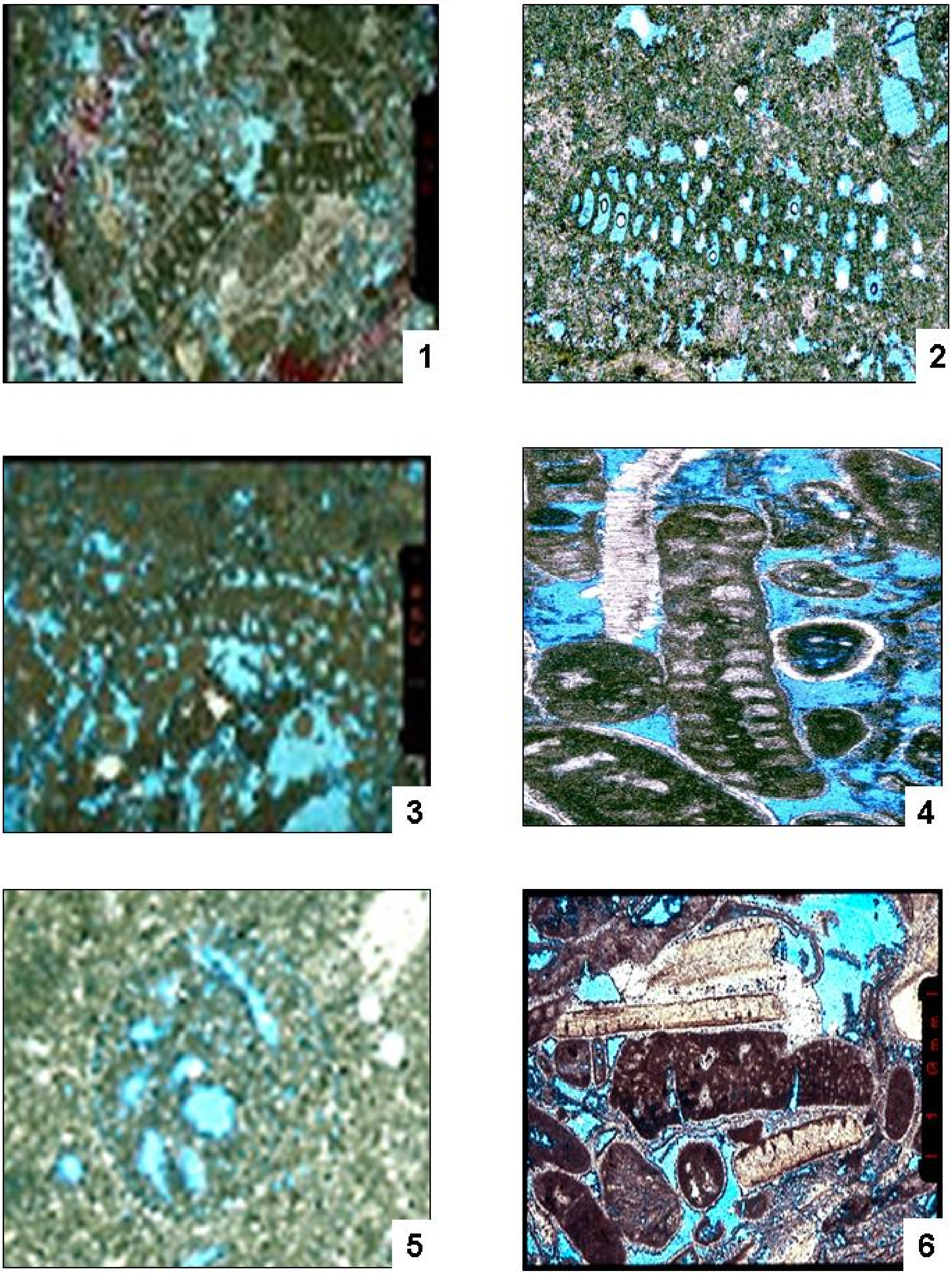

PLATE 3

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of Mangashtia viennoti, vertical section, FZRN well. (5X)

Figure 2. Photomicrograph of Mangashtia viennoti, vertical section, UTMN well. (5X)

Figure 3. Photomicrograph of Mangashtia viennoti, axial vertical section, Helwah section. (5X)

Figure 4. Photomicrograph of Mangashtia viennoti, tangential vertical section, KHRS well. (1.6X)

Figure 5. Photomicrograph of Alveosepta jacardi transverse section, ANDR well. (5X)

Figure6. Photomicrograph of Alveosepta jacardi tangential vertical section, KHRS well.(5X)

PLATE 4

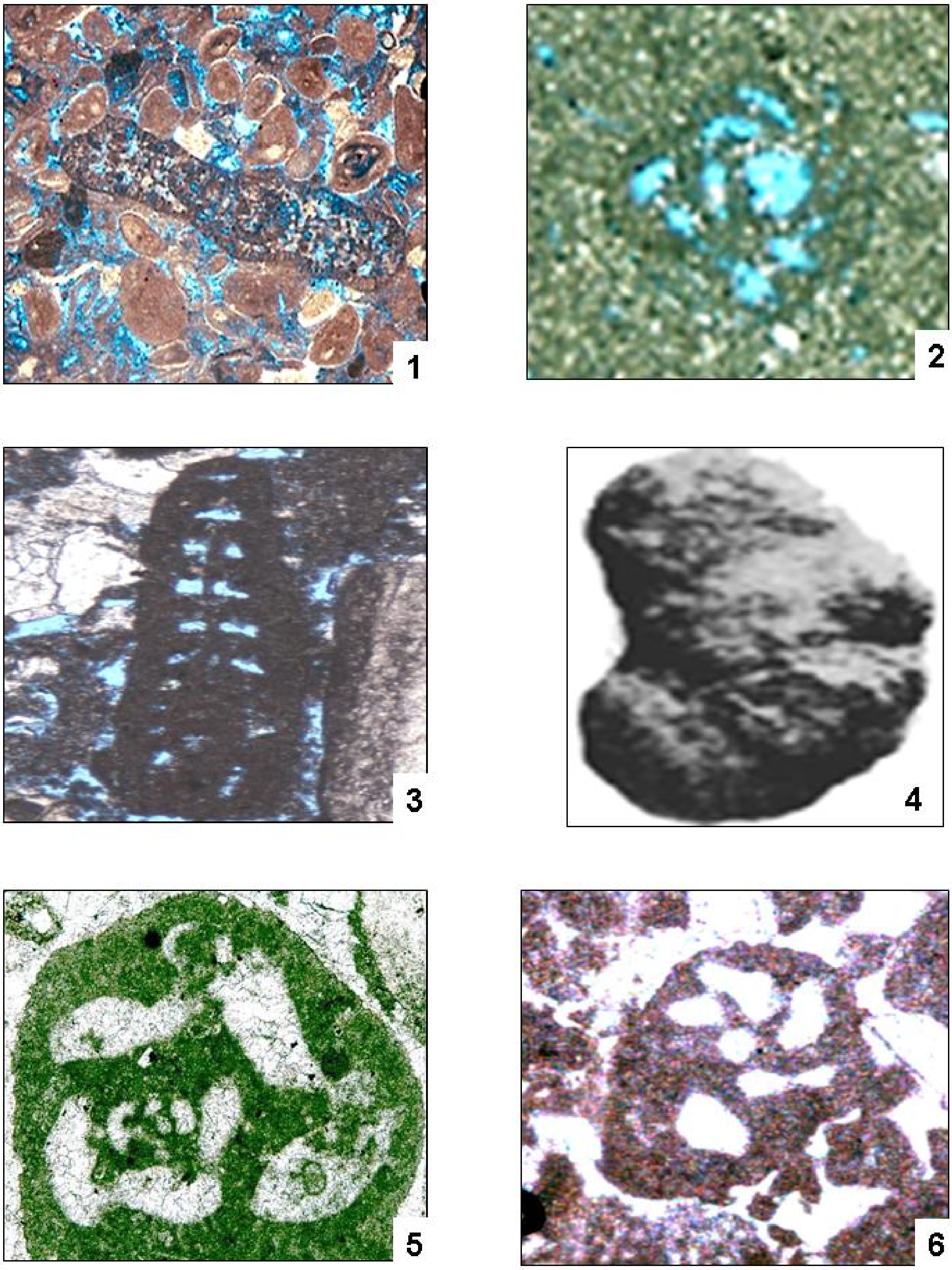

PLATE 4

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure1. Photomicrograph of *Alveosepta jacardi*, axial vertical section, HWYH well.(5X)

Figure 2. Photomicrograph of *Alveosepta jacardi* transverse section, ANDR well.(5X)

Figure 3. Photomicrograph of *Alveosepta jacardi* axial vertical section, HWYH well. (5X)

Figure 4. Photomicrograph of *Everticyclammina sp*. Redmond, 1964, lateral view. (5X)

Figure 5. Photomicrograph of *Everticyclammina sp*., transverse section, UTMN well. (10X)

Figure 6. Photomicrograph of *Everticyclammina sp*, transverse section, KHRS well. (5X)

PLATE 5

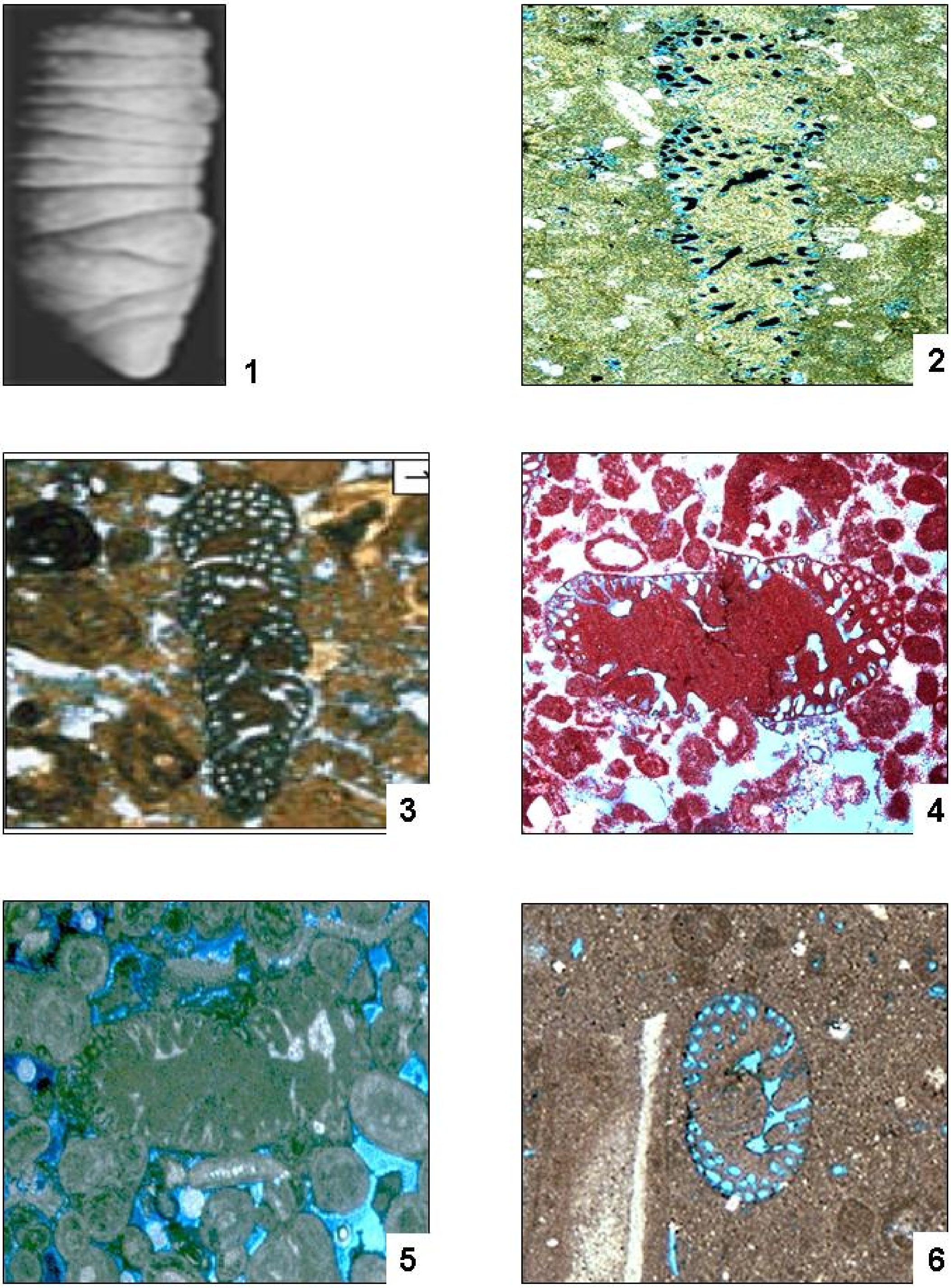

PLATE-5

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Kurnubia* Henson, 1948, lateral view. (5X)

Figure 2. Photomicrograph of *Kurnubia palastiniensis*, axial vertical section, HWYH well. (5X)

Figure 3. Photomicrograph of *Kurnubia palastiniensis*, axial vertical section, QTIF well. (5X)

Figure 4. Photomicrograph of *Kurnubia palastiniensis*, subaxial vertical section, KHRS well. (5X)

Figure 5. Photomicrograph of *Kurnubia palastiniensis*, oblique section, SDGM well. (5X)

Figure 6. Photomicrograph of *Kurnubia palastiniensis*, oblique subaxial vertical section FZRN well. (5X)

PLATE 6

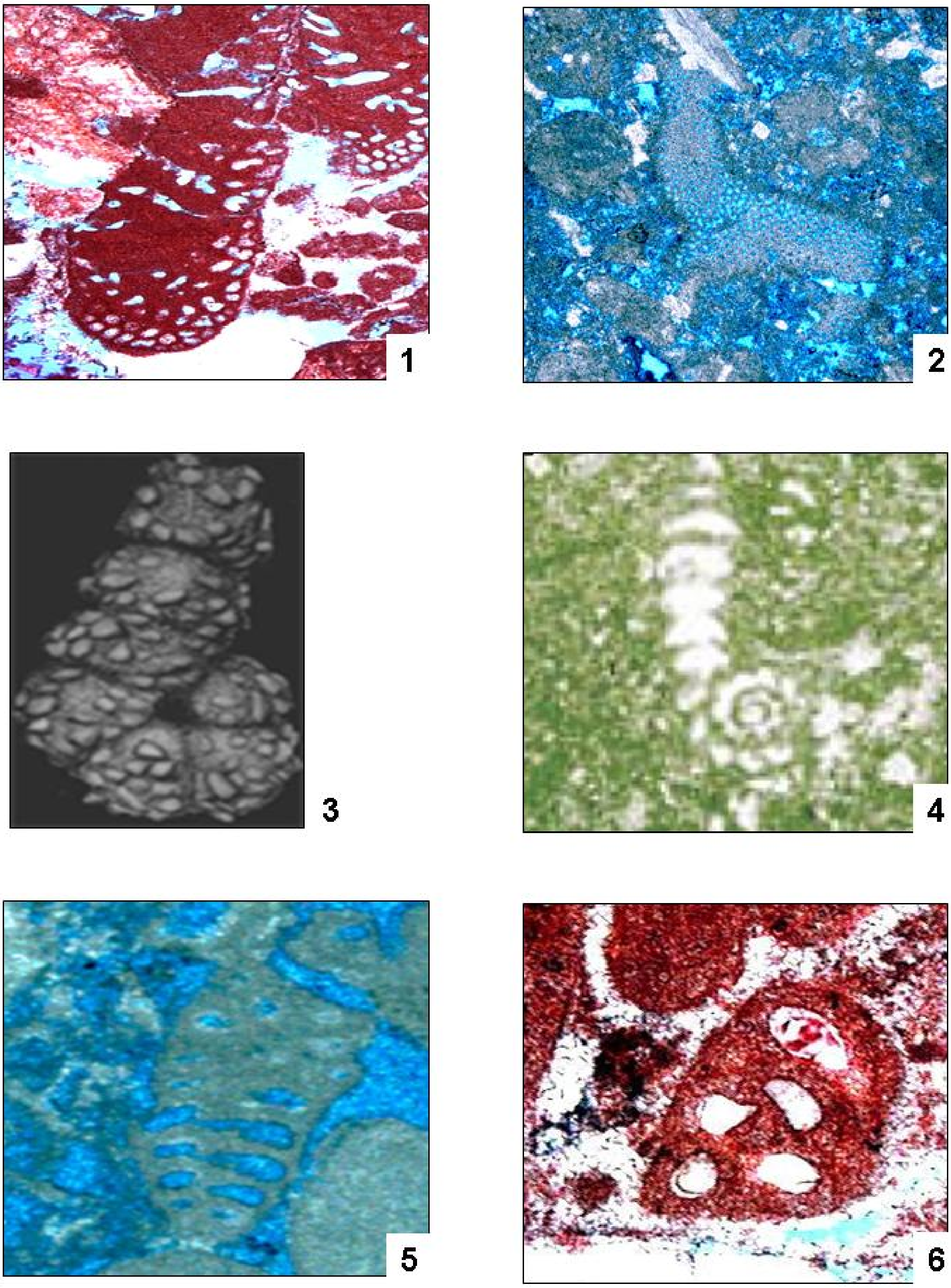

PLATE 6

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Kurnubia palastiniensis*, subaxial vertical section, KHRS well.(5X)

Figure 2. Photomicrograph of '*Kurnubia palastiniensis'*, unusual tangential vertical section, KHRS well. (1.6X)

Figure3. Photomicrograph of *Ammobaculites sp.* Cushman, 1910, lateral view. (5X)

Figure 4. Photomicrograph of *Ammobaculites sp.* vertical axial section, QTIF well. (5X)

Figure 5. Photomicrograph of *Redmondoides lugeoni,* vertical axial section, SDGM well. (5X)

Figure 6. Photomicrograph of *Redmondoides lugeoni,* oblique vertical axial section, QTIF well. (5X)

PLATE 7

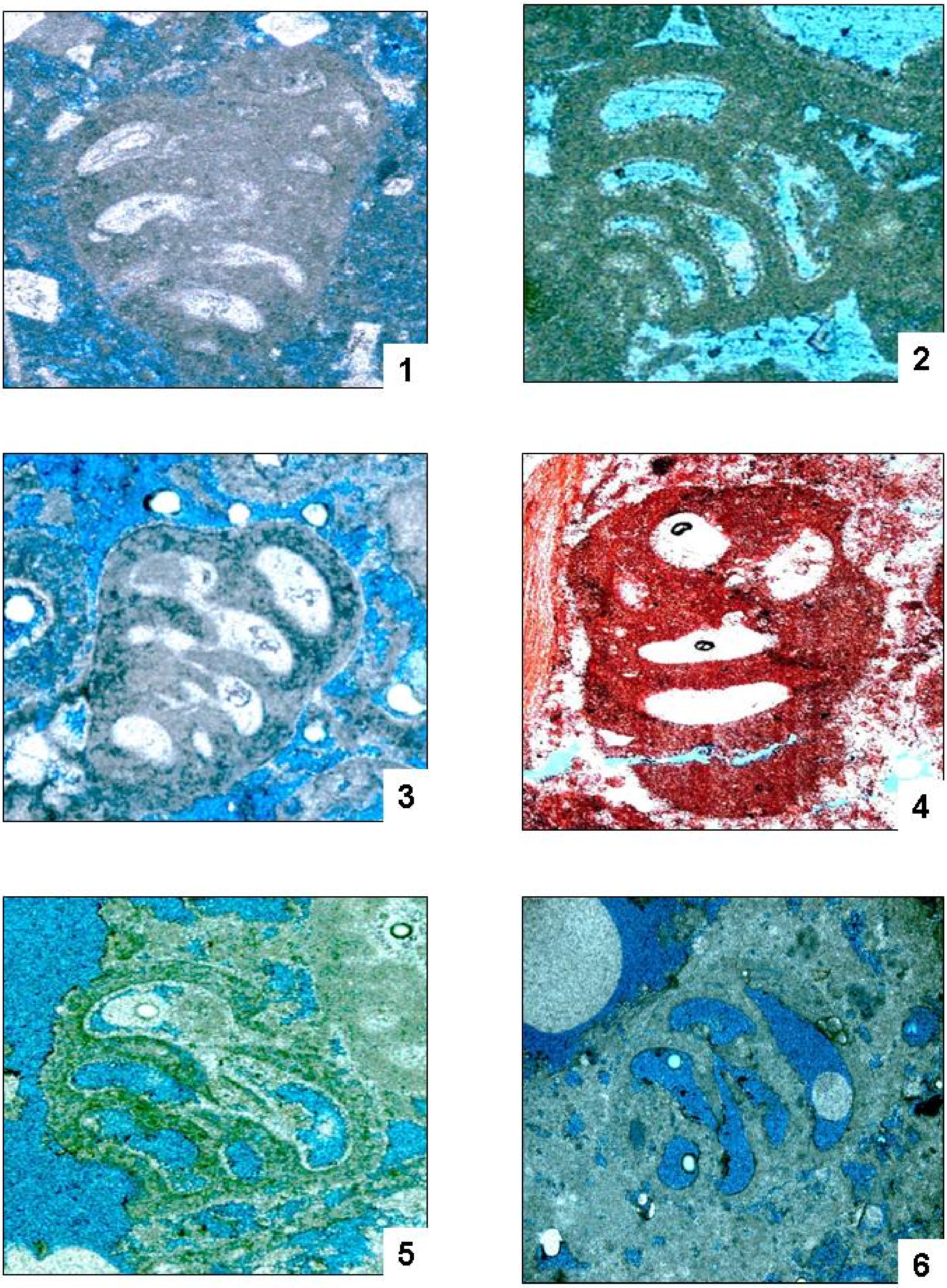

PLATE 7

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Redmondoides lugeoni*, vertical axial section, FZRN well. (5X)

Figure 2. Photomicrograph of *Redmondoides lugeoni*, vertical axial section, ANDR well. (5X)

Figure 3. Photomicrograph of *Redmondoides lugeoni*, vertical axial section, HWYH well. (5X)

Figure 4. Photomicrograph of *Redmondoides lugeoni*, oblique vertical axial section, UTMN well. (5X)

Figure 5. Photomicrograph of *Redmondoides lugeoni*, vertical axial section, FZRN well. (5X)

Figure 6. Photomicrograph of *Redmondoides lugeoni*, vertical axial section, QTIF well. (5X)

PLATE 8

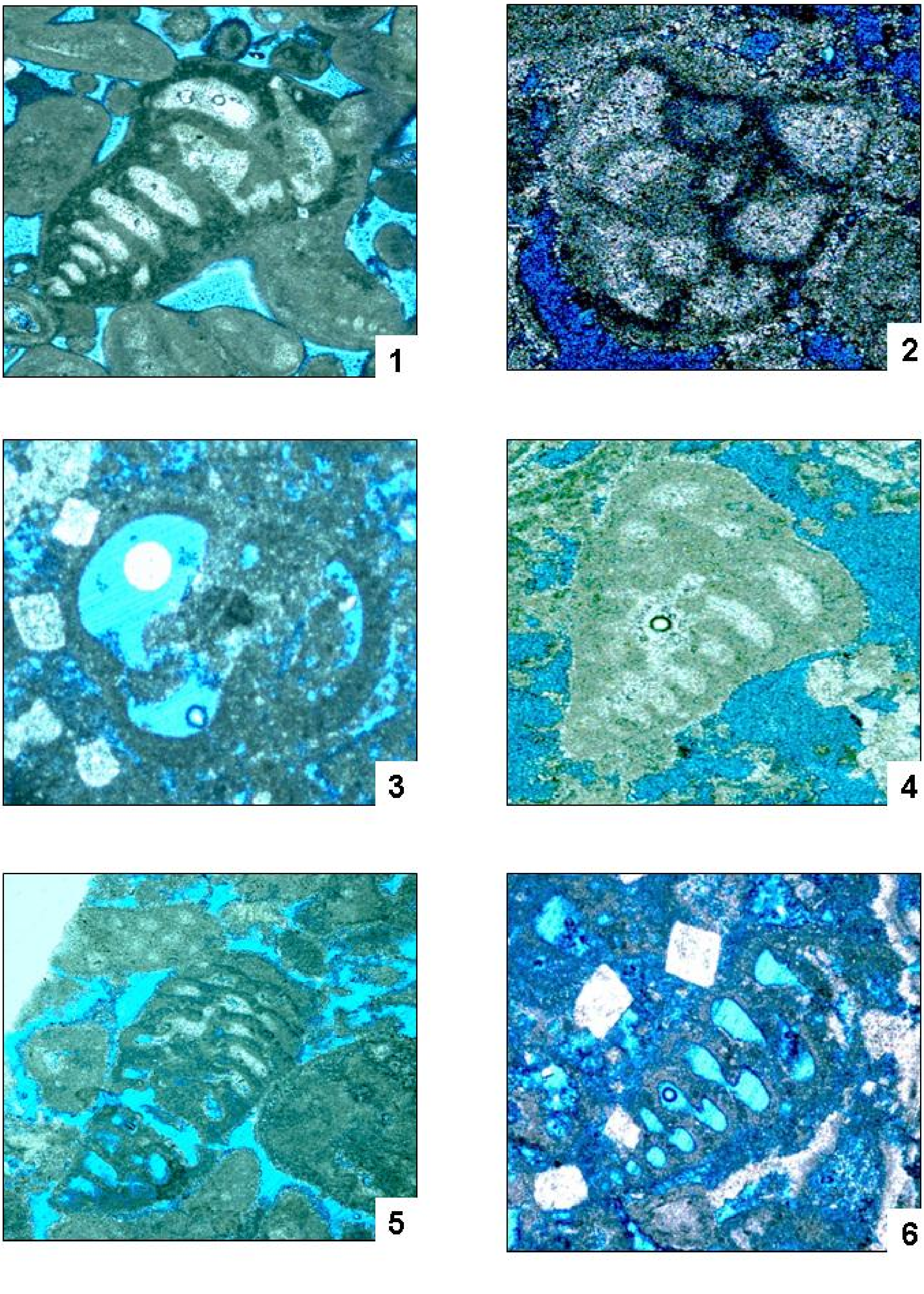

PLATE 8

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Redmondoides lugeoni,* vertical axial section, KHRS well. (5X)

Figure 2. Photomicrograph of *Redmondoides lugeoni,* oblique vertical axial section, HELWH section. (5X)

Figure 3. Photomicrograph of *Redmondoides lugeoni,* transverse section, FZRN well. (10X)

Figure 4. Photomicrograph of *Redmondoides lugeoni,* vertical axial section, ANDR well. (5X)

Figure 5. Photomicrograph of *Redmondoides lugeoni,* vertical axial section, FZRN well. (5X)

Figure 6. Photomicrograph of *Redmondoides lugeoni,* vertical axial section, QTIF well. (5X)

PLATE 9

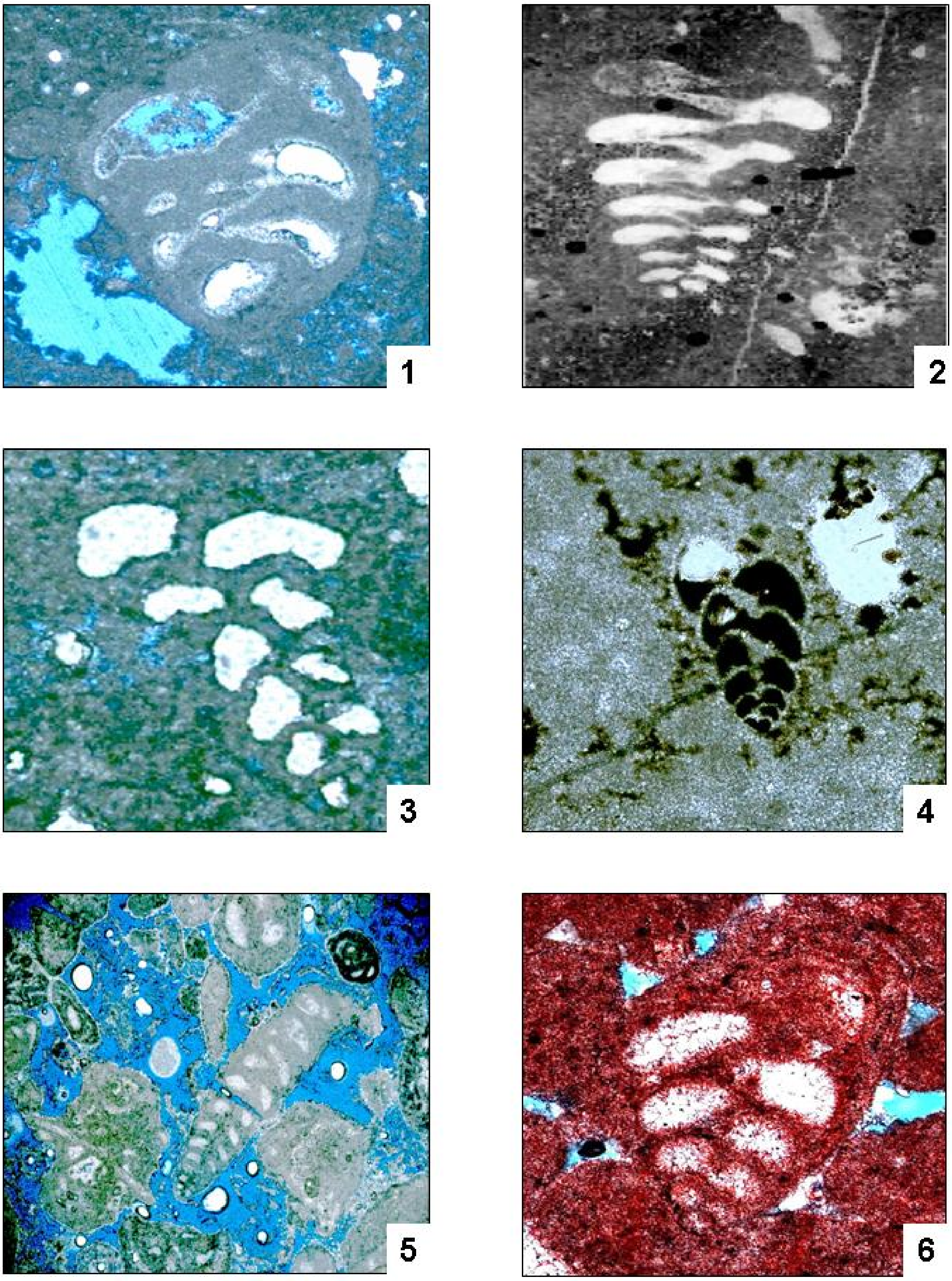

PLATE 9

PHOTOMICROGRAPH OF
AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Redmondoides lugeoni,* vertical axial section, FZRN well. (5X)

Figure 2. Photomicrograph of *Valvulina sp*., vertical axial section, FZRN well. (5X)

Figure 3. Photomicrograph of *Valvulina sp*., vertical axial section, KHRS well. (10X)

Figure 4. Photomicrograph of *Valvulina sp*., vertical axial section with residual oil blocked the chambers, QTIF well. (5X)

Figure 5. Photomicrograph of *Valvulina sp*., vertical axial section, ANDR well. (5X)

Figure6. Photomicrograph of *Textularia sp.,* vertical axial section, KHRS well. (5X)

PLATE 10

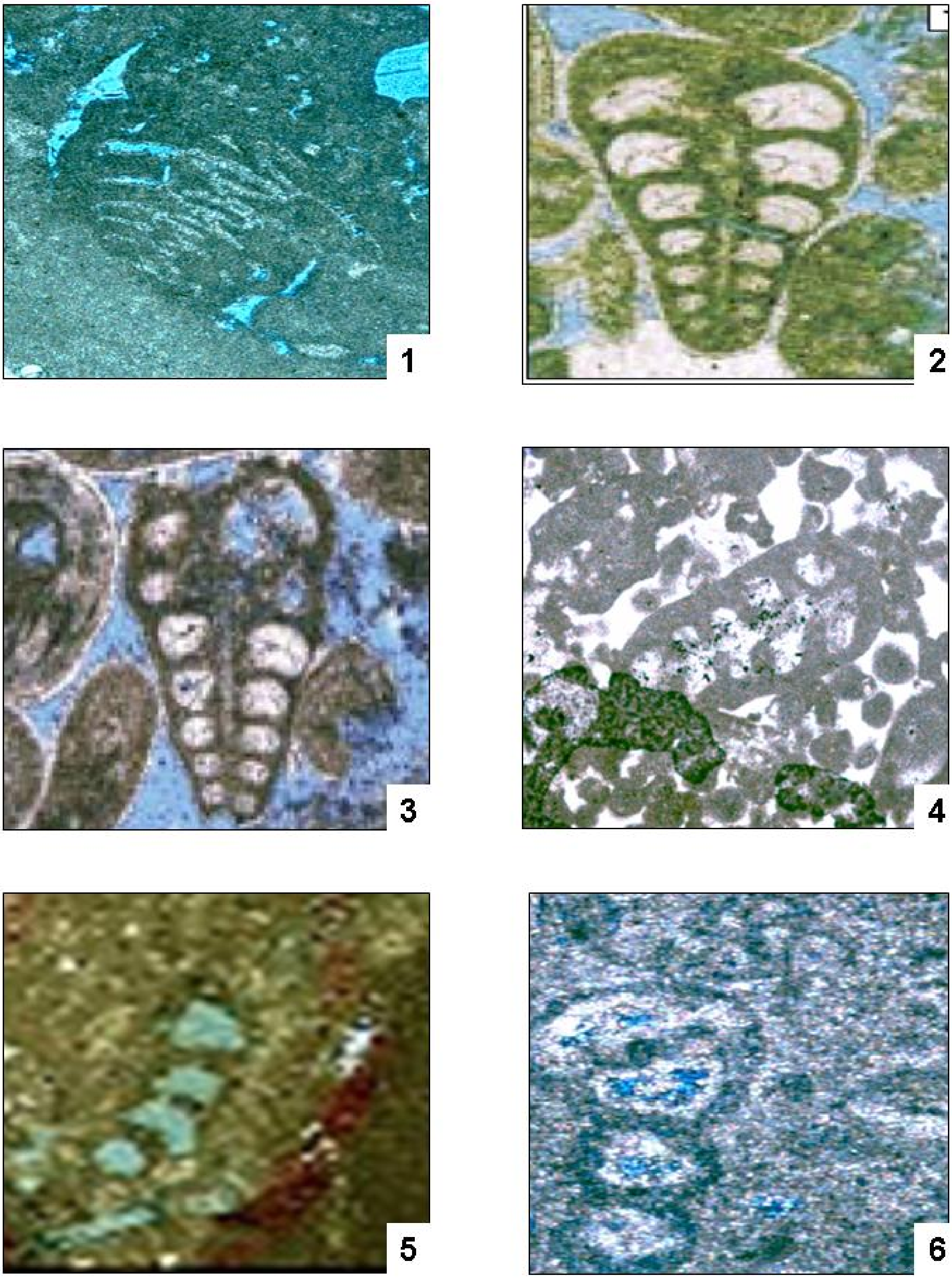

PLATE 10

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *'Praechrysalidina' sp*., vertical axial section, QTIF well. (5X)

Figure 2. Photomicrograph of *Siphovalvulina sp*., vertical axial section, HWYH well. (5X)

Figure 3. Photomicrograph of *Siphovalvulina sp*., vertical axial section, HWYH well. (5X)

Figure 4. Photomicrograph of *Reophax sp.,* vertical axial section, FZRN well. (5X)

Figure 5. Photomicrograph of agglutinated uniserial foraminifera, vertical axial section, HWYH well. (5X)

Figure 6. Photomicrograph of agglutinated uniserial foraminifera, vertical axial section, DQ section. (5X)

PLATE 11

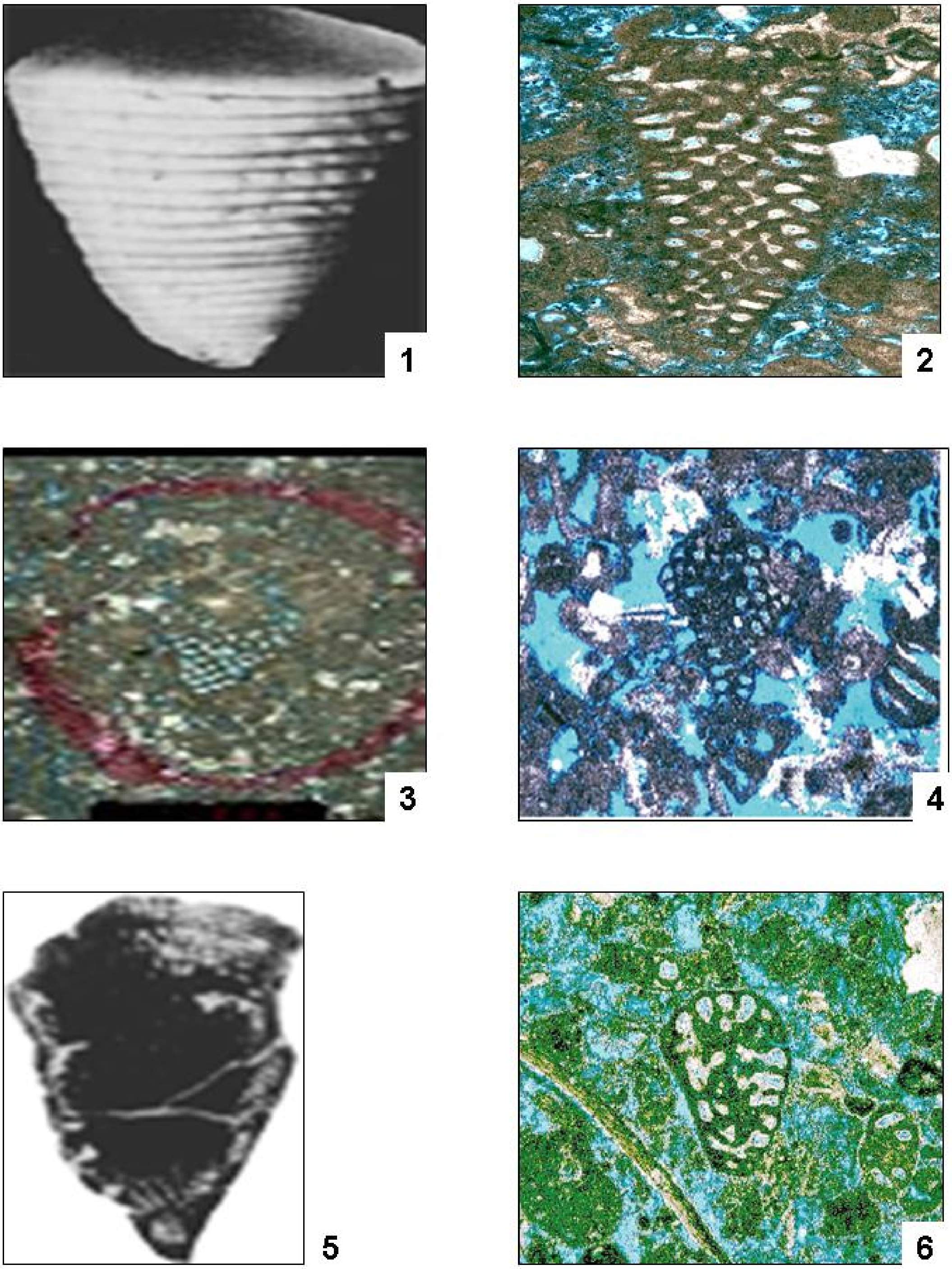

PLATE 11

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Iraqia sp*. Henson, 1948, lateral view.(5X)

Figure 2. Photomicrograph of *cf.Iraqia sp*., axial vertical section HWYH well.(5X)

Figure 3. Photomicrograph of *cf.Iraqia sp*., tangential vertical section, SDGM well.(5X)

Figure 4. Photomicrograph of *cf.Iraqia sp*., subaxial vertical section, UTMN well.(5X)

Figure 5. Photomicrograph of *Satorina sp*., Fourcade and Chorowicz, 1980 axial vertical section. (5X)

Figure 6. Photomicrograph of *cf. Satorina sp*., oblique axial section, UTMN well. (5X)

PLATE 12

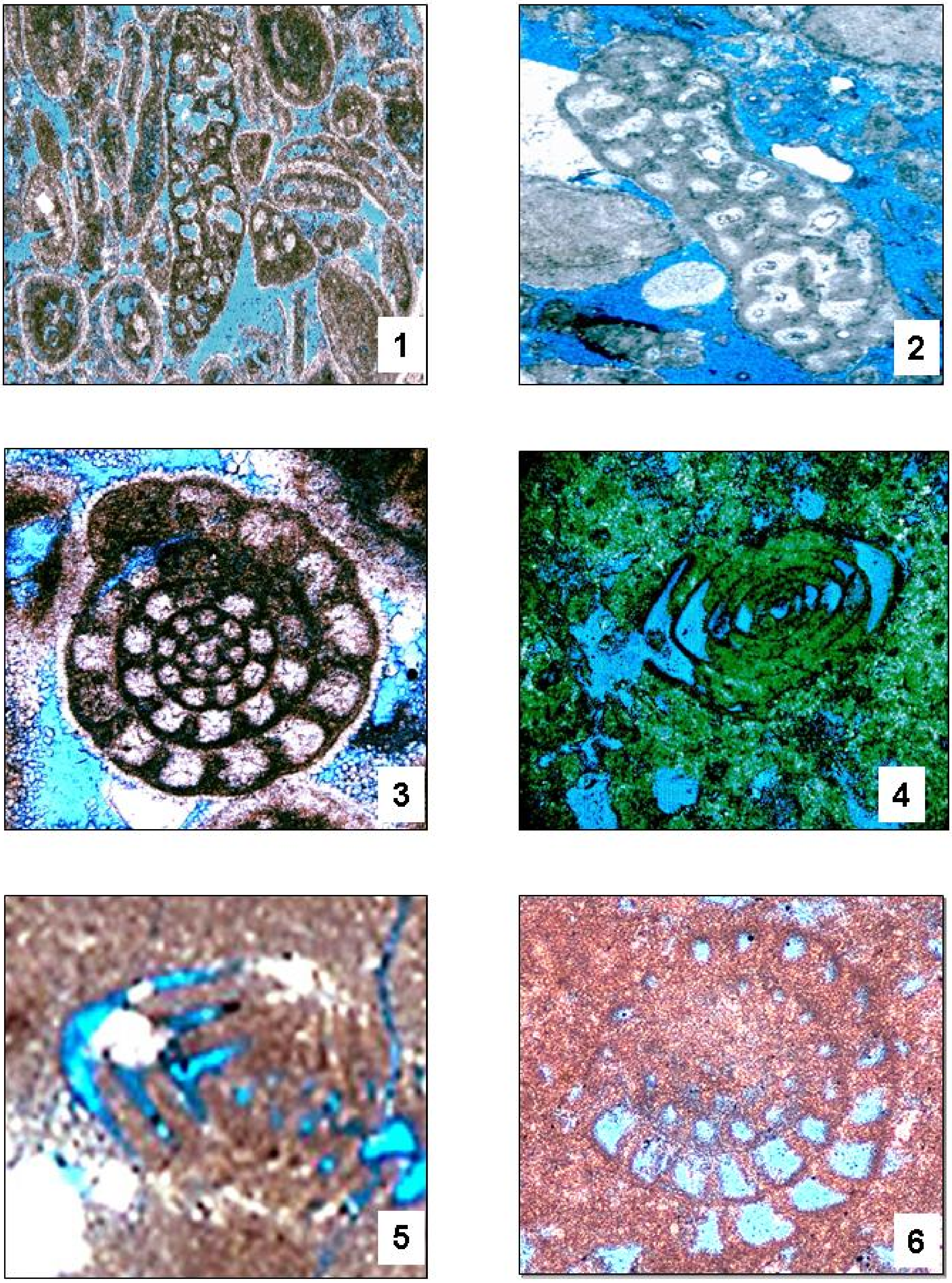

PLATE 12

PHOTOMICROGRAPH OF AGGLUTINATED BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *cf. Satorina sp*., axial vertical section, UTMN well. (5X)

Figure 2. Photomicrograph of *cf. Satorina sp*., subaxial vertical section, KHRS well. (5X)

Figure 3. Photomicrograph of *Nautiloculina oolithica*, tangential vertical section, HWYH well.(5X)

Figure 4. Photomicrograph of *Nautiloculina oolithica*, axial section, ANDR well. (5X)

Figure 5. Photomicrograph of *Nautiloculina oolithica*, oblique section, QTIF well. (5X).

Figure 6. Photomicrograph of *Nautiloculina oolithica*, tangential vertical section, ANDR well. (5X)

PLATE 13

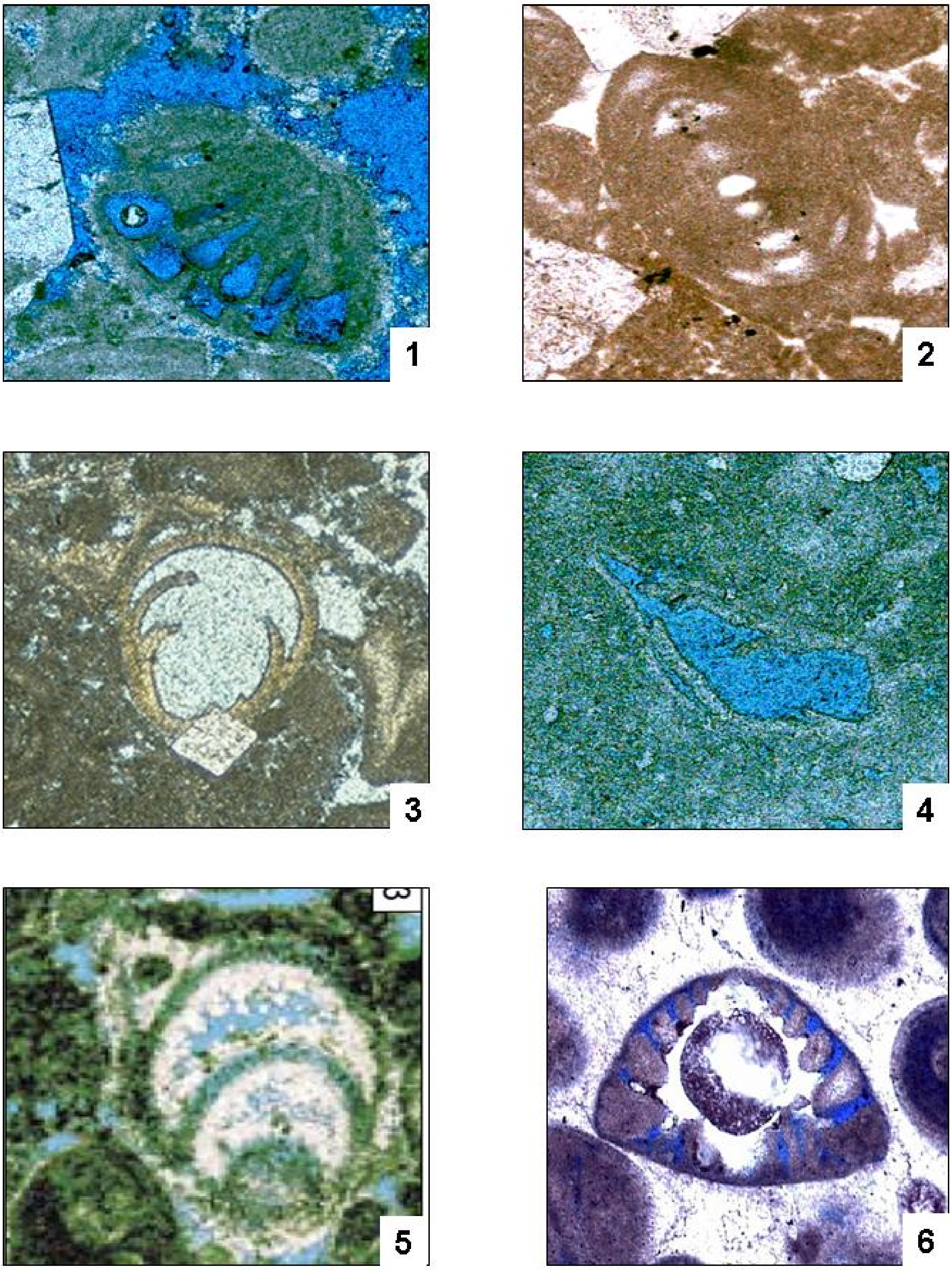

PLATE 13

PHOTOMICROGRAPH OF
AGGLUTINATED AND CALCAREOUS BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Nautiloculina oolithica*, oblique transverse section, ABSF well. (5X)

Figure 2. Photomicrograph of *Nautiloculina oolithica*, axial section, HWYH well. (5X)

Figure 3. Photomicrograph of *Polymorphinid sp*., axial section, SDGM well. (10X)

Figure 4. Photomicrograph of *Polymorphinid sp*., compacted axial section, FZRN well. (10X)

Figure 5. Photomicrograph of *Polymorphinid sp*., axial section, HWYH well. (10X)

Figure 6. Photomicrograph of *Trocholina alpina*, vertical axial section, KHRS well. (5X)

PLATE 14

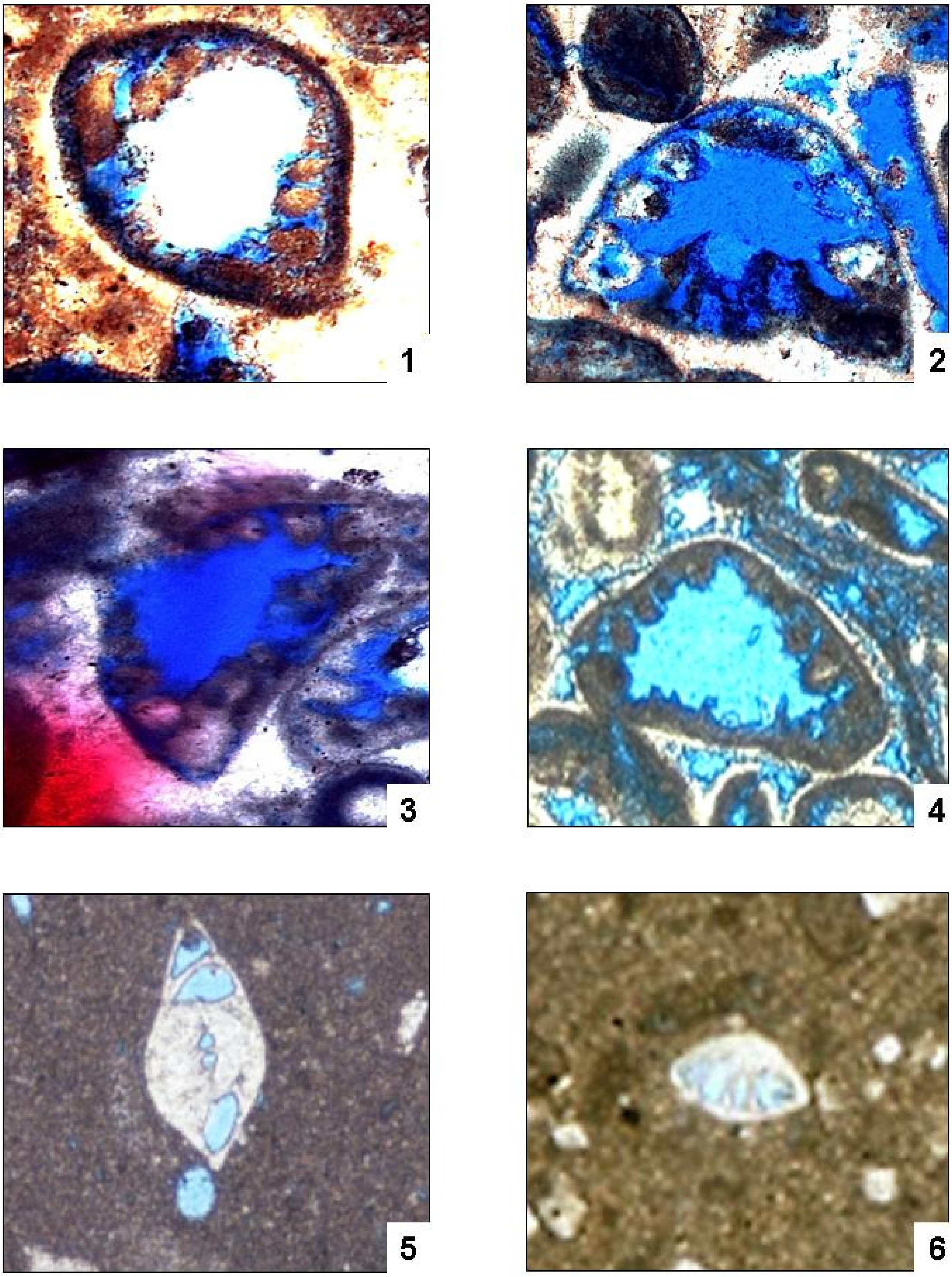

PLATE 14

PHOTOMICROGRAPH OF CALCAREOUS BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Trocholina alpina*, tangential vertical axial section, HWYH well. (5X)

Figure 2. Photomicrograph of *Trocholina alpina*, tangential vertical axial section, QTIF well. (5X)

Figure 3. Photomicrograph of *Trocholina alpina*, tangential vertical axial section, FZRN well. (5X)

Figure 4. Photomicrograph of *Trocholina alpina*, tangential vertical axial section, UTMN well. (5X)

Figure 5. Photomicrograph of *Lenticulina sp*., transverse section HWYH well. (X10)

Figure 6. Photomicrograph

PLATE 15

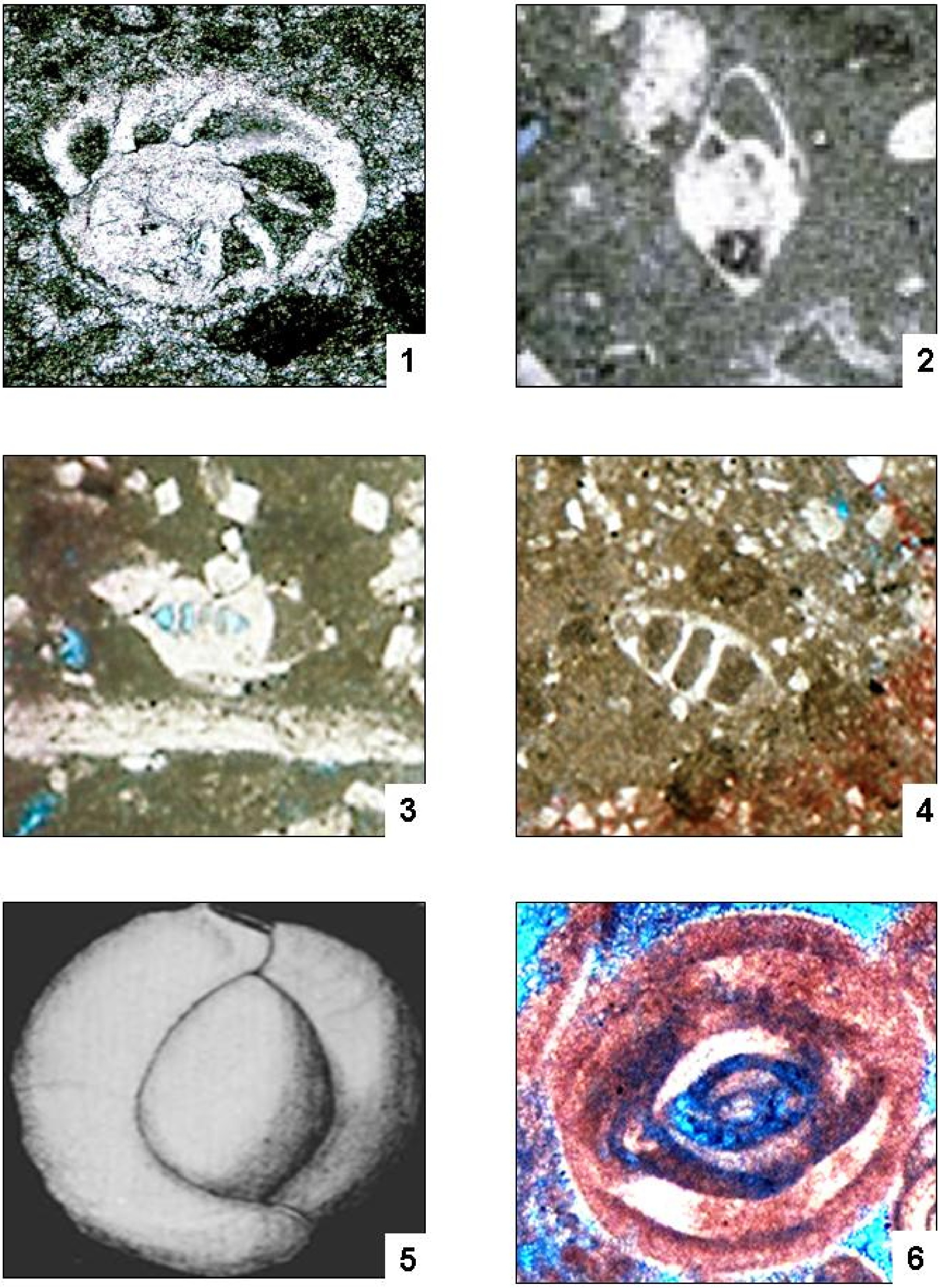

PLATE 15

PHOTOMICROGRAPH OF
CALCAREOUS AND MILIOLID BENTHONIC FORAMINIFERA

Figure 1. Photomicrograph of *Lenticulina sp*., oblique axial section, HWYH well. (10X)

Figure 2. Photomicrograph of *Lenticulina sp*., axial vertical section, UTMN well. (10X)

Figure 3. Photomicrograph of *Lenticulina sp*. axial vertical section, FZRN well. (10X)

Figure 4. Photomicrograph of *Lenticulina sp.,* tangential vertical section, FZRN well.(10X)

Figure 5. Photomicrograph of *Quinqueloculina sp.,* d'Orbigny, 1826, lateral view. (5X)

Figure 6. Photomicrograph of *Quinqueloculina sp*., vertical axial section, QTIF well. (10X)

PLATE 16

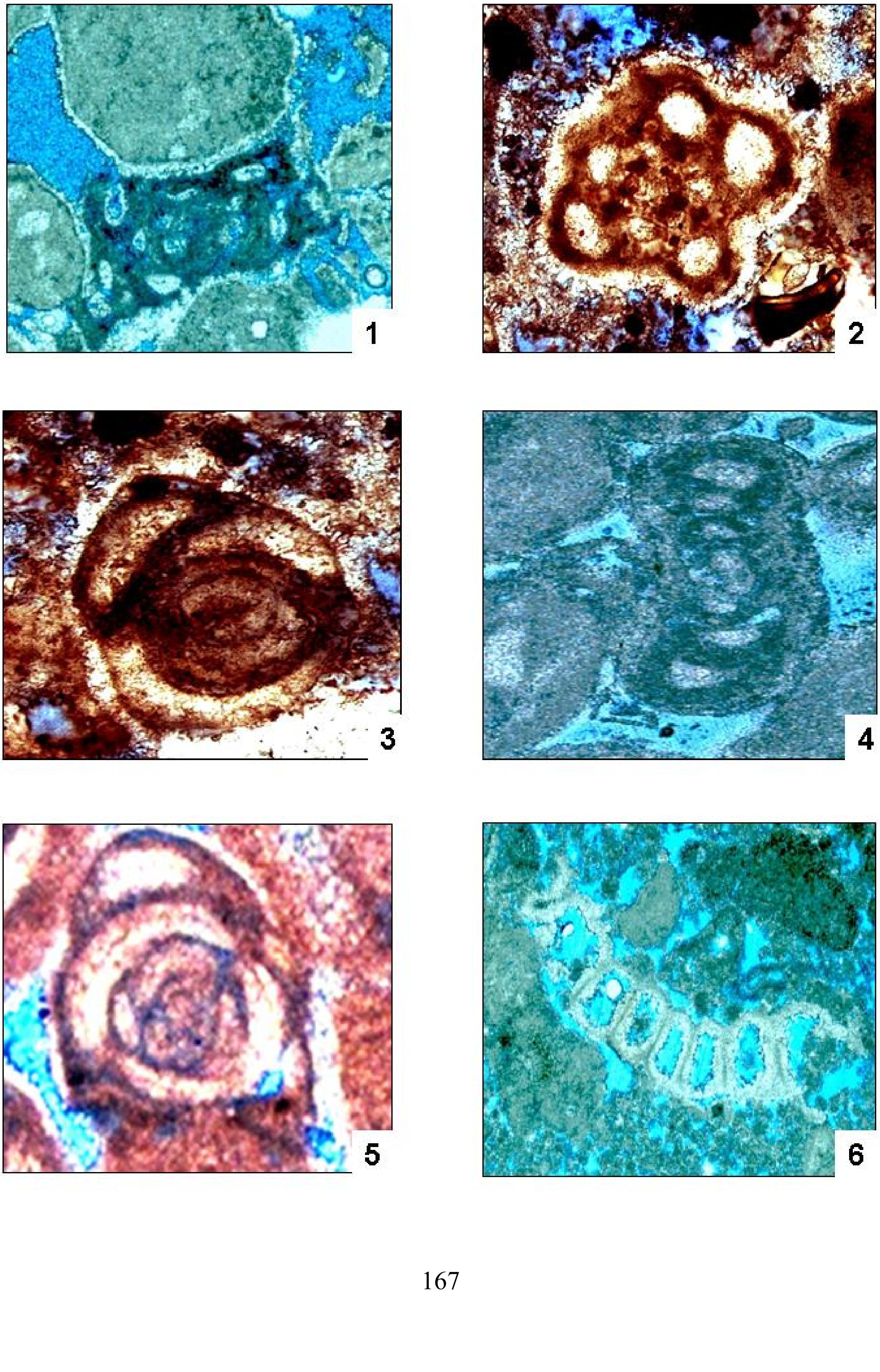

PLATE 16

PHOTOMICROGRAPH OF
MILIOLID FORAMINIFERA AND CALCAREOUS ALGAE

Figure 1. Photomicrograph of *Quinqueloculina sp*. compacted transverse section, UTMN well. (5X)

Figure 2. Photomicrograph of *Quinqueloculina sp*. transverse section, Okala section. (5X)

Figure 3. Photomicrograph of *Quinqueloculina sp*. vertical axial section, Okala section. (5X)

Figure 4. Photomicrograph of *Quinqueloculina sp*. oblique transverse section, QTIF well. (5X)

Figure 5. Photomicrograph of *Quinqueloculina sp*., oblique vertical axial section, KHRS well. (5X)

Figure 1. Photomicrograph of *Clypeina jurassica* fragment, SDGM well (5X).

PLATE 17

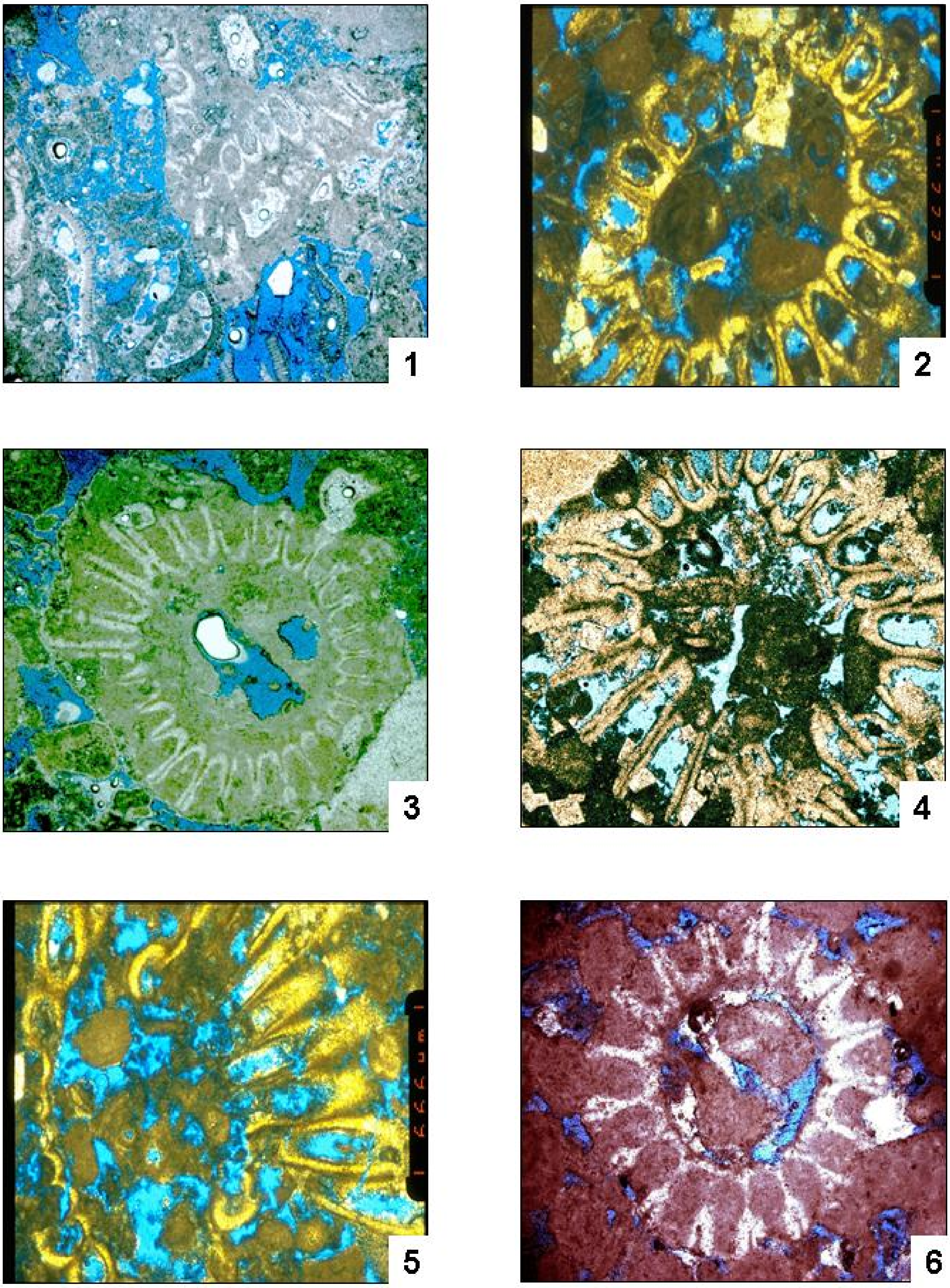

PLATE 17

PHOTOMICROGRAPH OF CALCAREOUS ALGAE

Figure 1. Photomicrograph of *Clypeina jurassica* oblique section, QTIF well. (5X)

Figure 2. Photomicrograph of *Clypeina jurassica* transverse section of entire disc, KHRS well. (1.6X)

Figure 3. Photomicrograph of *Clypeina jurassica* transverse section of entire disc, SDGM well. (1.6X)

Figure 4. Photomicrograph of *Clypeina jurassica* transverse section of entire disc, UTMN well. (1.6X)

Figure 5. Photomicrograph of *Clypeina jurassica* Tangential transverse section of entire disc, KHRS well.(1.6X)

Figure 6. Photomicrograph of *Clypeina jurassica* transverse section of entire disc, FZRN well. (1.6X)

PLATE 18

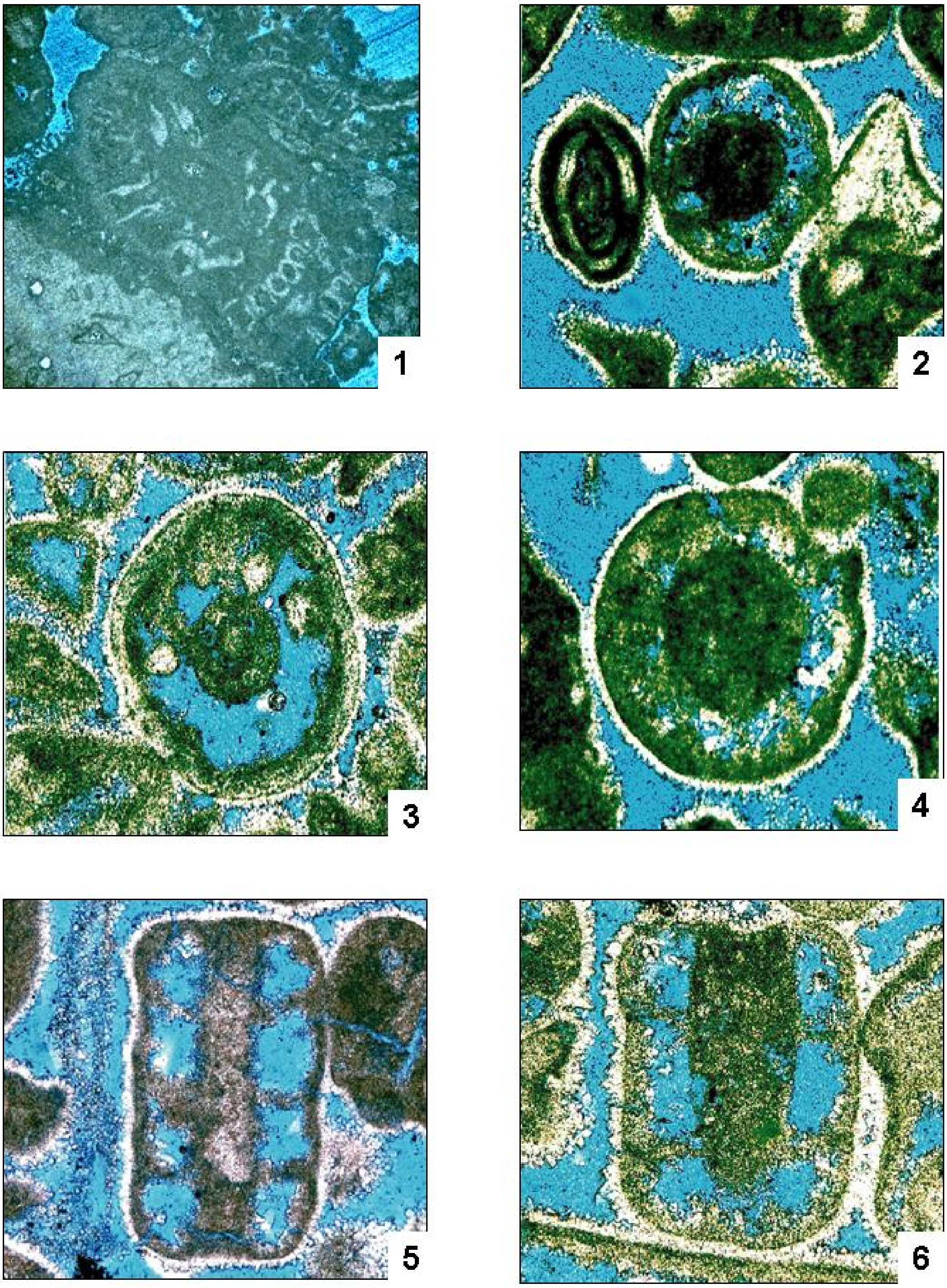

PLATE 18

PHOTOMICROGRAPH OF CALCAREOUS ALGAE

Figure 1. Photomicrograph of *Clypeina jurassica* oblique section, FZRN well. (5X)

Figure 2. Photomicrograph of *Salpingoporella annulata,* transverse section with *Quinqueloculina sp*., HWYH well. (5X)

Figure 3. Photomicrograph of *Salpingoporella annulata,* transverse section, HWYH well.(5X)

Figure 4. Photomicrograph of *Salpingoporella annulata,* transverse section, HWYH. (5X)

Figure 5. Photomicrograph of *Salpingoporella annulata,* axial vertical, HWYH well.(5X)

Figure 6. Photomicrograph of *Salpingoporella annulata,* axial vertical, HWYH well.(5X)

PLATE 19

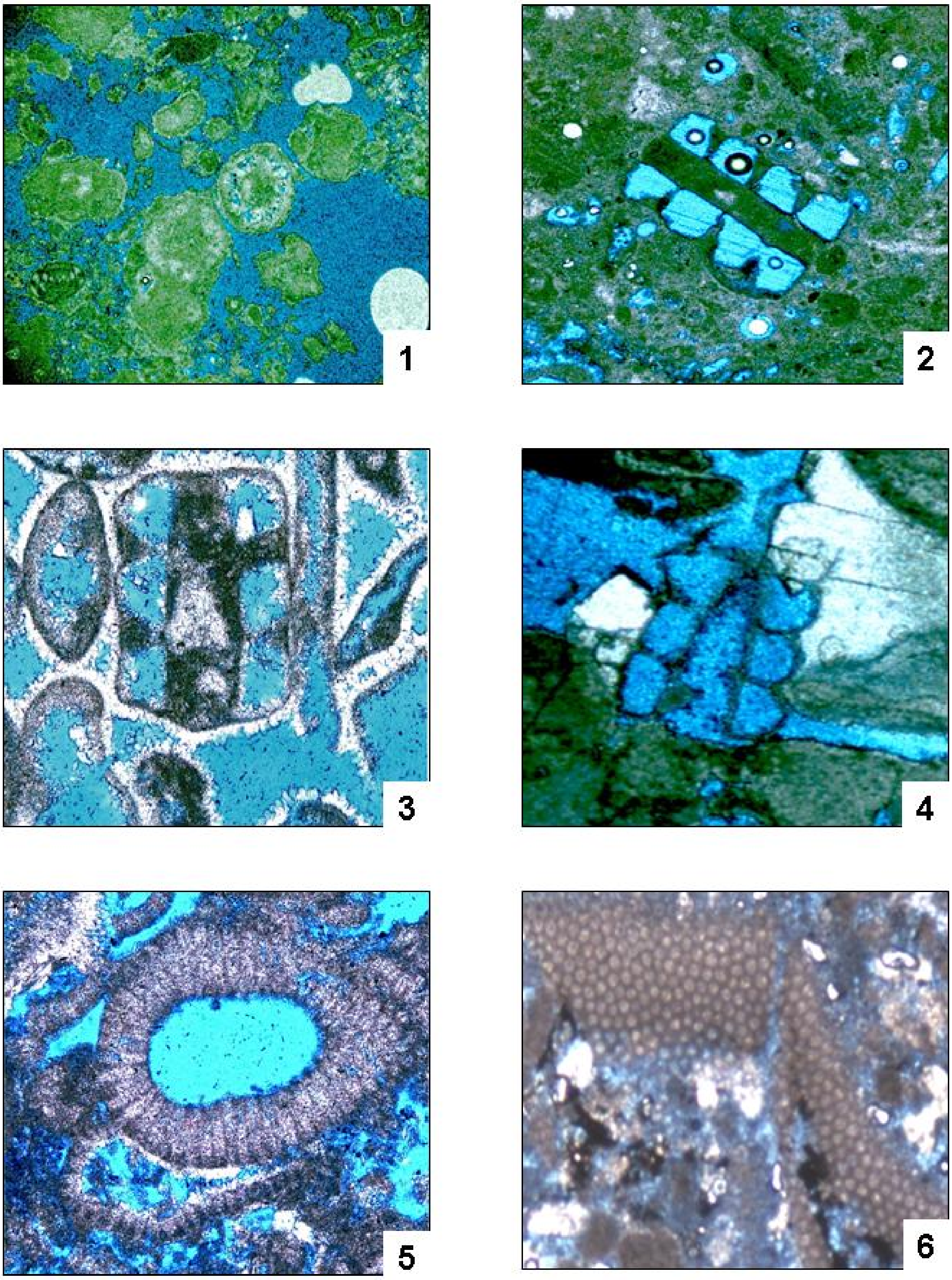

PLATE 19

PHOTOMICROGRAPH OF CALCAREOUS ALGAE

Figure 1. Photomicrograph of *Salpingoporella annulata,* transverse section, Okala section.(5X)

Figure 2. Photomicrograph of *Salpingoporella annulata,* axial vertical, FZRN well.(5X)

Figure 3. Photomicrograph of *Salpingoporella annulata,* axial vertical, HWYH well.(5X)

Figure 4. Photomicrograph of *Salpingoporella annulata,* oblique axial vertical, KHRS well.(5X)

Figure 5. Photomicrograph of *Thaumatoporella parvovesciculifera*, HWYH well.(5X)

Figure 6. Photomicrograph of *Thaumatoporella parvovesciculifera*, KHRS well.(5X)

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PLATE 20

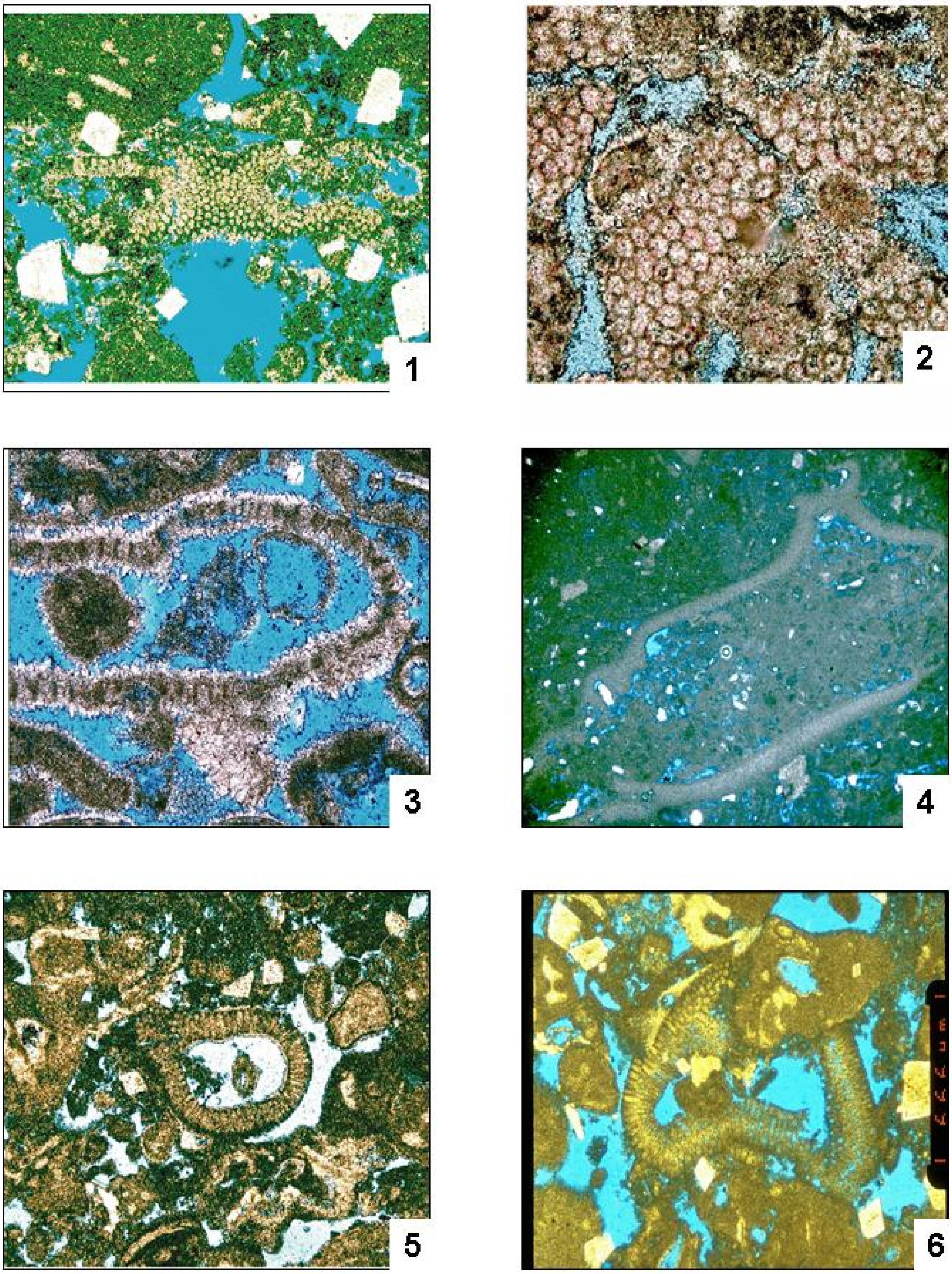


PLATE 20

PHOTOMICROGRAPH OF CALCAREOUS ALGAE

Figure 1.Photomicrograph of *Thaumatoporella parvovesciculifera*, ABSF well. (5X)

Figure 2. Photomicrograph of *Thaumatoporella parvovesciculifera*, HWYH well.(5X)

Figure 3. Photomicrograph of *Thaumatoporella parvovesciculifera*, DQ section. (5X)

Figure 4. Photomicrograph of *Thaumatoporella parvovesciculifera*, UTMN well. (5X)

Figure 5. Photomicrograph of *Thaumatoporella parvovesciculifera*, UTMN well. (5X)

Figure 6. Photomicrograph of *Thaumatoporella parvovesciculifera*, FZRN well. (5X)

PLATE 21

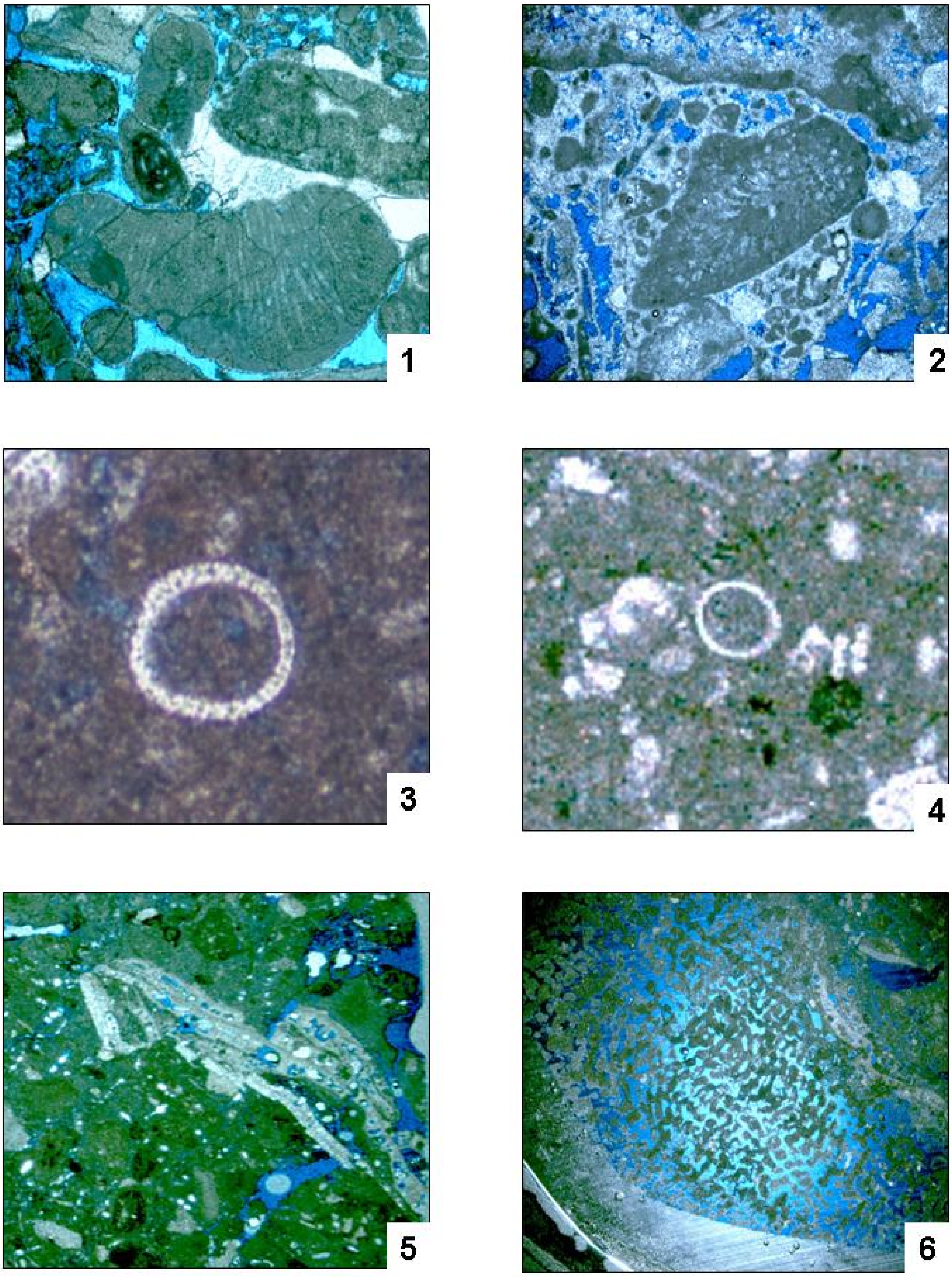


PLATE 21

PHOTOMICROGRAPH OF
CALCAREOUS ALGAE AND STROMATOPOROIDS

Figure 1. Photomicrograph of *Cayeuxia* s*p*., HWYH well. (5X)

Figure 2. Photomicrograph of *Cayeuxia* sp. *(Arabicodium sp*.), FZRN well. (5X)

Figure 3. Photomicrograph of Calcisphere, HWYH well. (10X)

Figure 4. Photomicrograph of Calcisphere, SDGM well.(10X)

Figure 5. Photomicrograph of *Burgundia sp*., (encrusting / layered stromatoporoid) with monaxon sponge spicules, SDGM well. (1.6X)

Figure 6. Photomicrograph of *Burgundia sp*., KHRS well.(1.6X)

PLATE 22

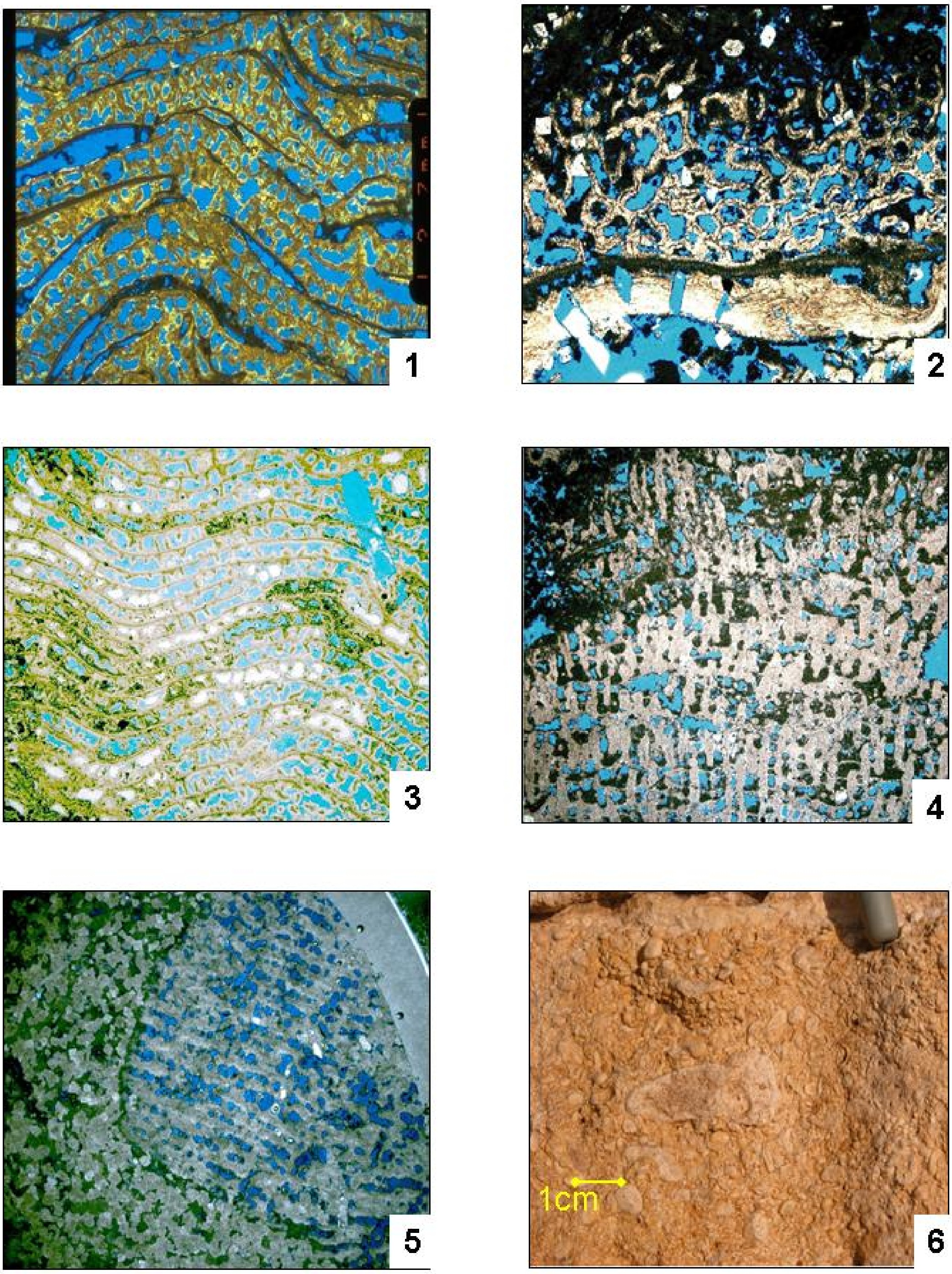


PLATE 22

PHOTOMICROGRAPH OF STROMATOPOROIDS

Figure 1. Photomicrograph of *Burgundia sp*., UTMN well.(1.6X)

Figure 2. Photomicrograph of *Burgundia sp*., with brachipod debris, UTMN well.(1.6X)

Figure 3. Photomicrograph of *Burgundia sp*., HWYH well.(1.6X)

Figure 4. Photomicrograph of *Burgundia sp*., HWYH well.(1.6X)

Figure 5. Photomicrograph of *Burgundia sp*., ANDR well.(1.6X)

Figure 6. Photomicrograph of *Cladocoropsis mirabilis* (branching stromatoporoid) in oncolitic grainstone, DQ section.

PLATE 23

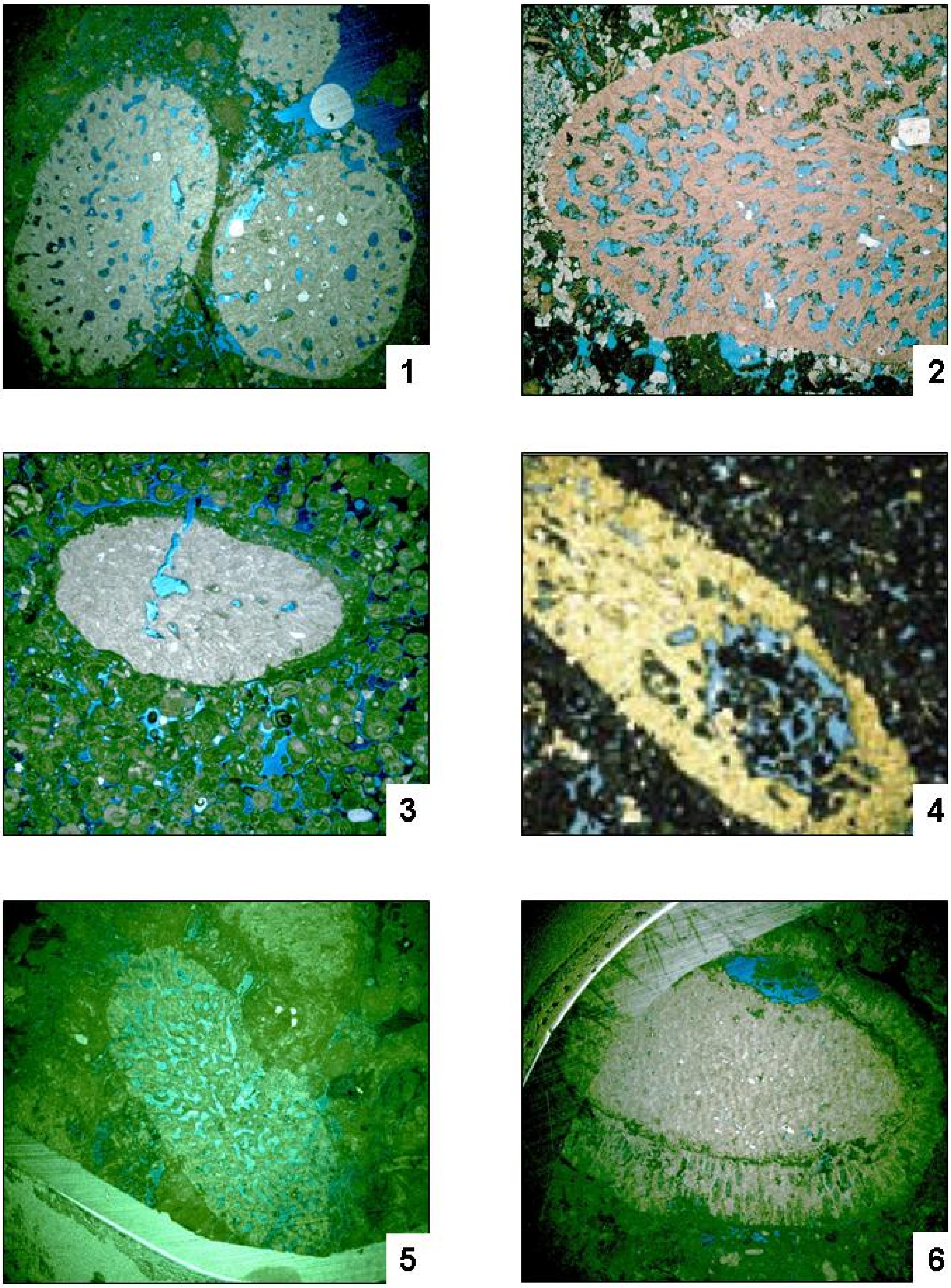


PLATE 23

PHOTOMICROGRAPH OF STROMATOPOROIDS

Figure 1. Photomicrograph of *Cladocoropsis mirabilis*, transverse section, FZRN well. (1.6X)

Figure 2. Photomicrograph of *Cladocoropsis mirabilis*, axial section, HWYH well. (1.6X)

Figure 3. Photomicrograph of *Cladocoropsis mirabilis*, transverse section, KHRS well. (1.6X)

Figure 4. Photomicrograph of *Cladocoropsis mirabilis*, oblique axial section, HWYH. (1.6X)

Figure 5. Photomicrograph of *Cladocoropsis mirabilis*, oblique axial section, SDGM well (1.6X)

Figure 6. Photomicrograph of *Cladocoropsis mirabilis* with encrusting bryozoan

PLATE 24

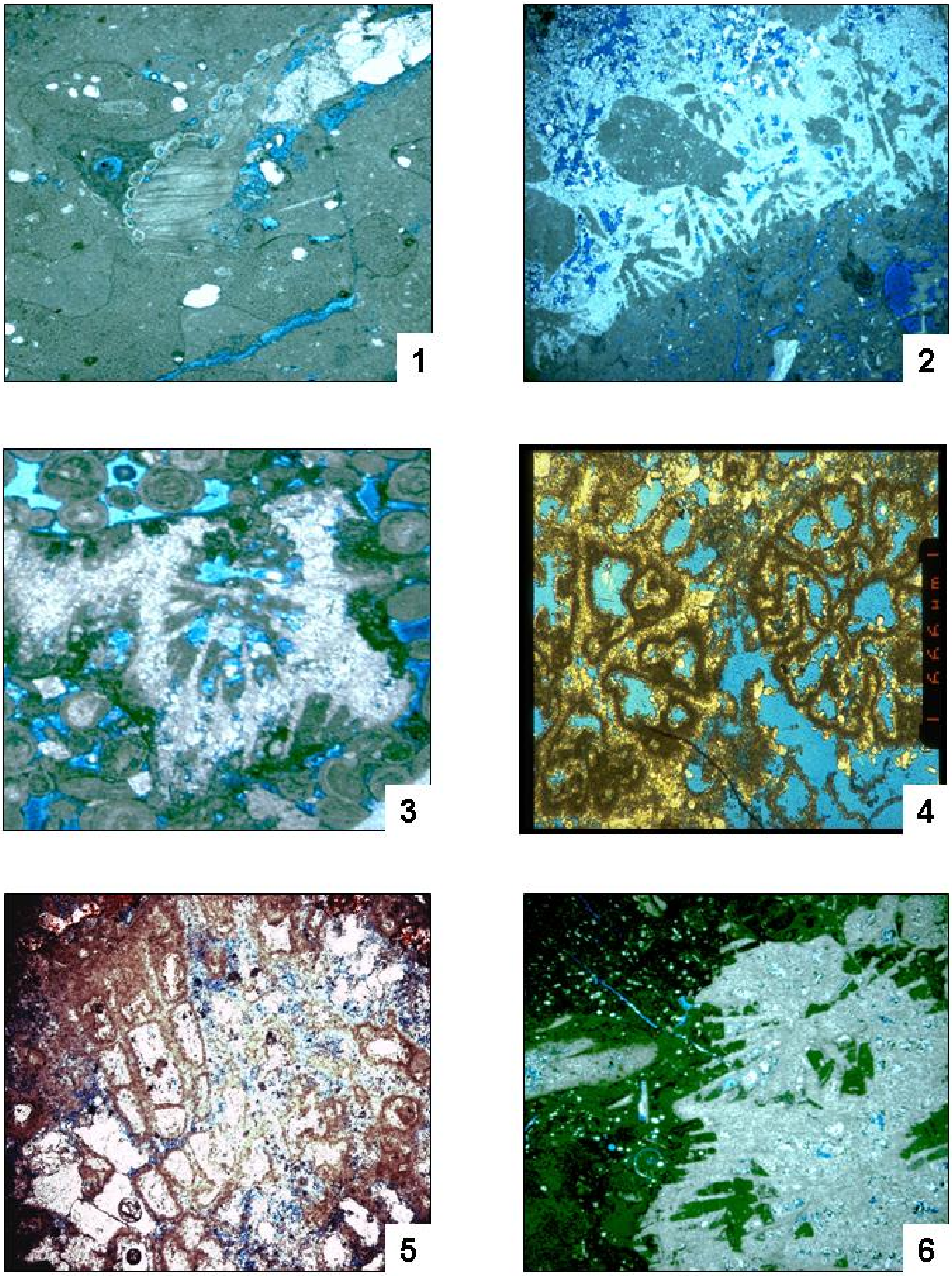


PLATE-24

PHOTOMICROGRAPH OF BRYOZOAN AND CORAL FRAGMENTS

Figure 1. Photomicrograph of bryozoan debris, FZRN well. (1.6)

Figure 2. Photomicrograph of coral fragment, ANDR well.(1.6X)

Figure 3. Photomicrograph of coral fragment, transverse section, ANDR well.(1.6X)

Figure 4. Photomicrograph of coral fragment, transverse section, HWYH well. (1.6X)

Figure 5. Photomicrograph of coral fragment, oblique section, KHRS well. (1.6X)

Figure 6. Photomicrograph of coral fragment, transverse section, KHRS well. (1.6X)

PLATE 25

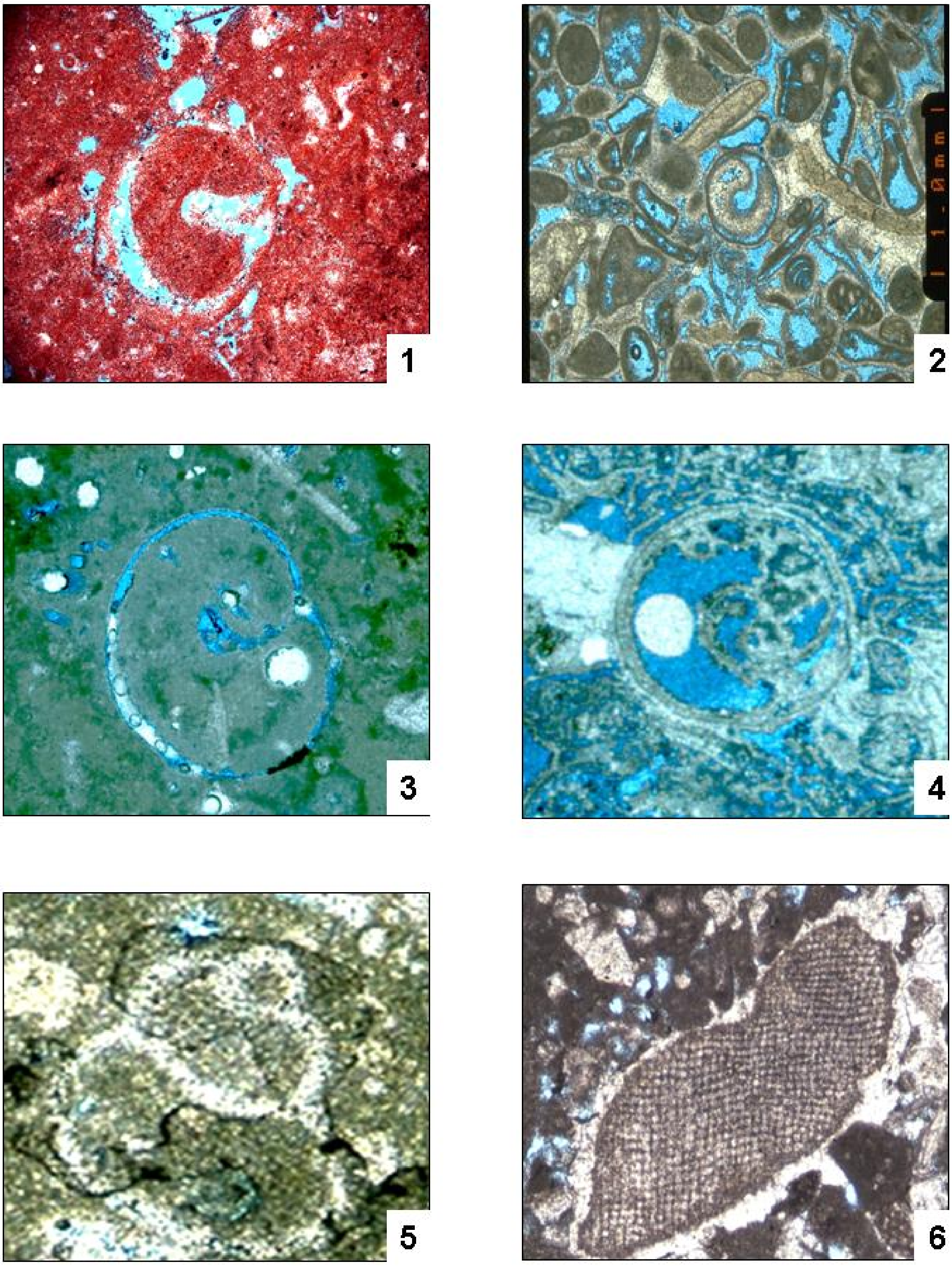


PLATE 25

PHOTOMICROGRAPH OF GASTROPODS AND ECHINOID FRAGMENTS

Figure 7. Photomicrograph of cerithid gastropod transverse section, KHRS well.(5X)

Figure 8. Photomicrograph of cerithid gastropod transverse section, QATIF well. (1.6X)

Figure 10. Photomicrograph of cerithid gastropod tangential transverse section, FZRN well. (5X)

Figure 11. Photomicrograph of cerithid gastropod transverse section, Okla section. (5X)

Figure 9. Photomicrograph of cerithid gastropod vertical axial section, HELWH section. (5X)

Figure 12. Photomicrograph of echinoid plate fragment, HWYH well. (5X)

PLATE 26

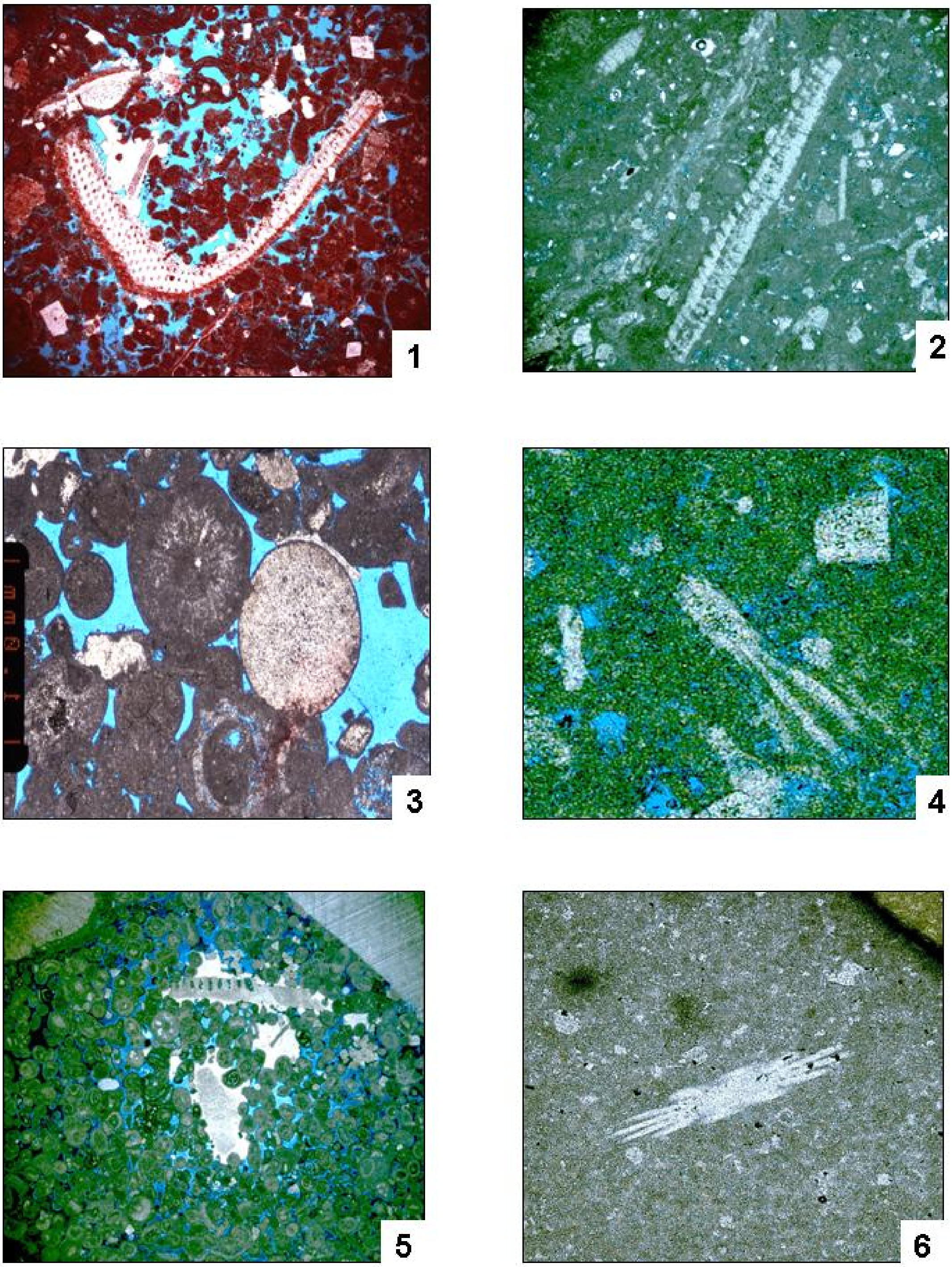


PLATE-26

PHOTOMICROGRAPH OF ECHINOID FRAGMENTS

Figure 1. Photomicrograph of echinoid plate debris, QTIF well. (1.6X)

Figure 2. Photomicrograph of echinoid debris, FZRN well. (1.6X)

Figure 3. Photomicrograph of echinoid spine transverse section with *Salpingoporella annulata*, SDGM well. (5X)

Figure 4. Photomicrograph of echinoid spine transverse section with finely ribbed, FZRN well. (5X)

Figure 5. Photomicrograph of echinoid debris with syntaxially calcite overgrowth, FZRN well. (1.6X)

Figure 6. Photomicrograph of echinoid spine oblique transverse section, QTIF well (5X)

PLATE 27

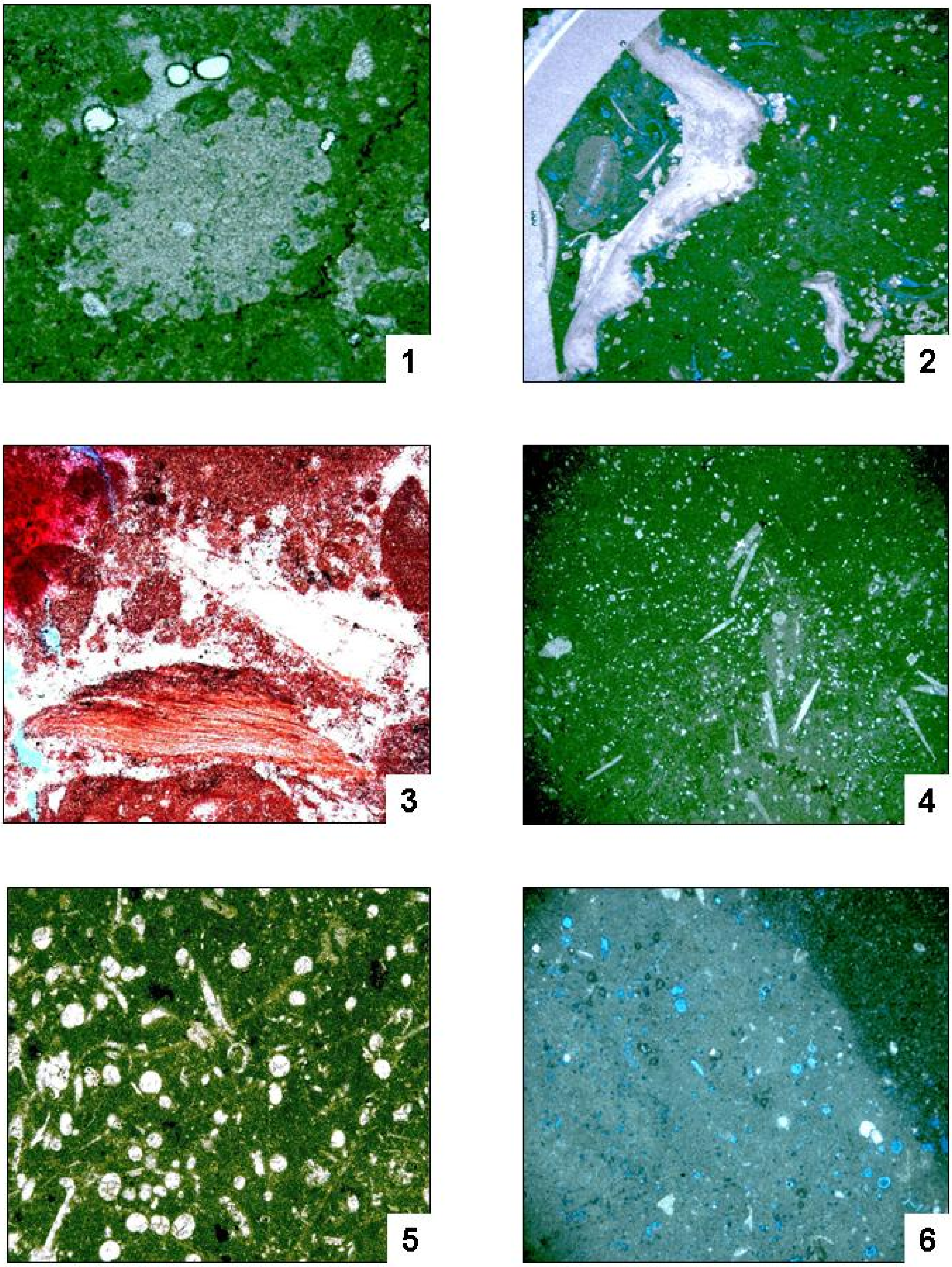


PLATE 27

PHOTOMICROGRAPH OF
ECHINOID SPINE, BRACHIOPOD AND SPONGE SPICULES

Figure1. Photomicrograph of echinoid spine transverse section (fine ›12 ribs), FZRN well. (10X)

Figure 2. Photomicrograph of brachiopod debris with pseudopunctate shell, FZRN well. (1.6X)

Figure 3. Photomicrograph of brachiopod debris, ABSF well. (5X)

Figure 4. Photomicrograph of monaxon sponge spicules, QTIF well. (X5)

Figure 5. Photomicrograph of monaxon sponge spicules, FZRN well. (5X)

Figure 6. Photomicrograph of monaxon sponge spicules, DQ well. (5X)

PLATE 28

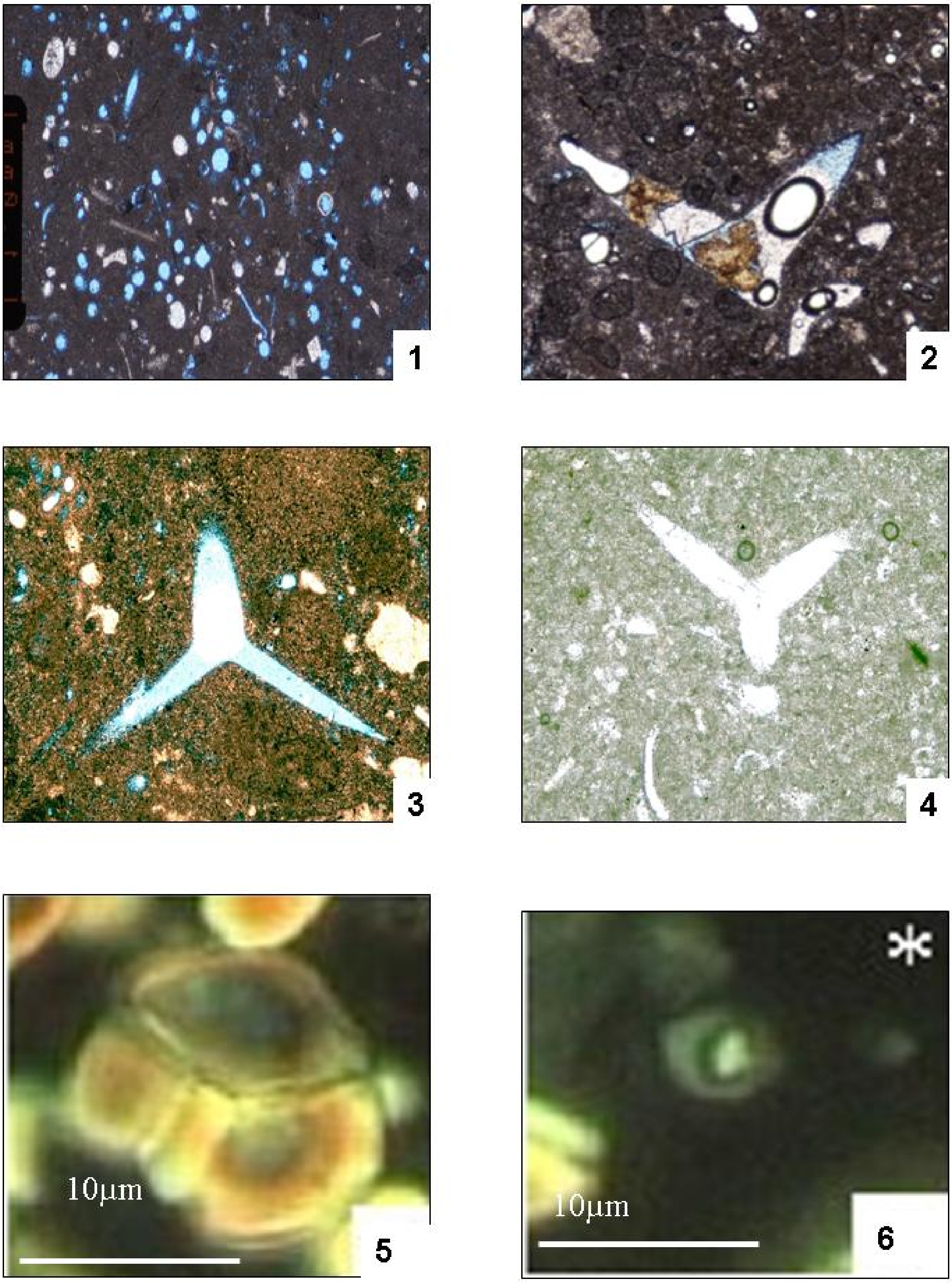


PLATE 28

PHOTOMICROGRAPH OF
SPONGE SPICULES AND CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of monaxon sponge spicules, HWYH well. (X10)

Figure 2. Photomicrograph of tetraxon sponge spicules FZRN well. (10X)

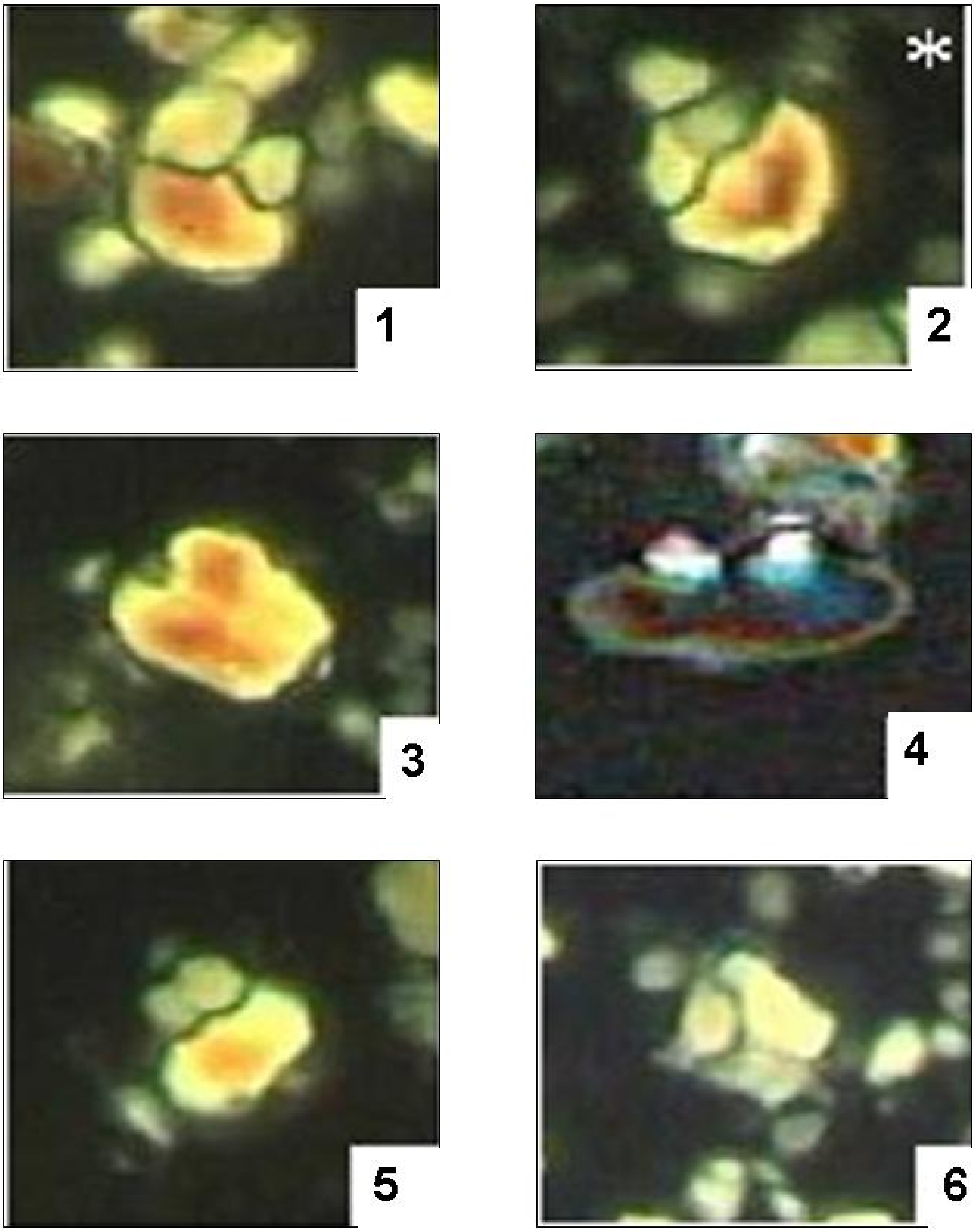
Figure 3. Photomicrograph of tetraxon sponge spicules HWYH well. (10X)

Figure 4. Photomicrograph of tetraxon sponge spicules, DQ section. (10X)

Figure 5. Photomicrograph of *Disechinatus clausus*, under cross-polarized light

Figure 6. Photomicrograph of *Ommalithus clarus*, under cross-polarized light

PLATE 29



10μm

PLATE 29

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Disechinatus selenion*, under cross-polarized light

Figure 2. Photomicrograph of *Disechinatus clausus*, under cross-polarized light

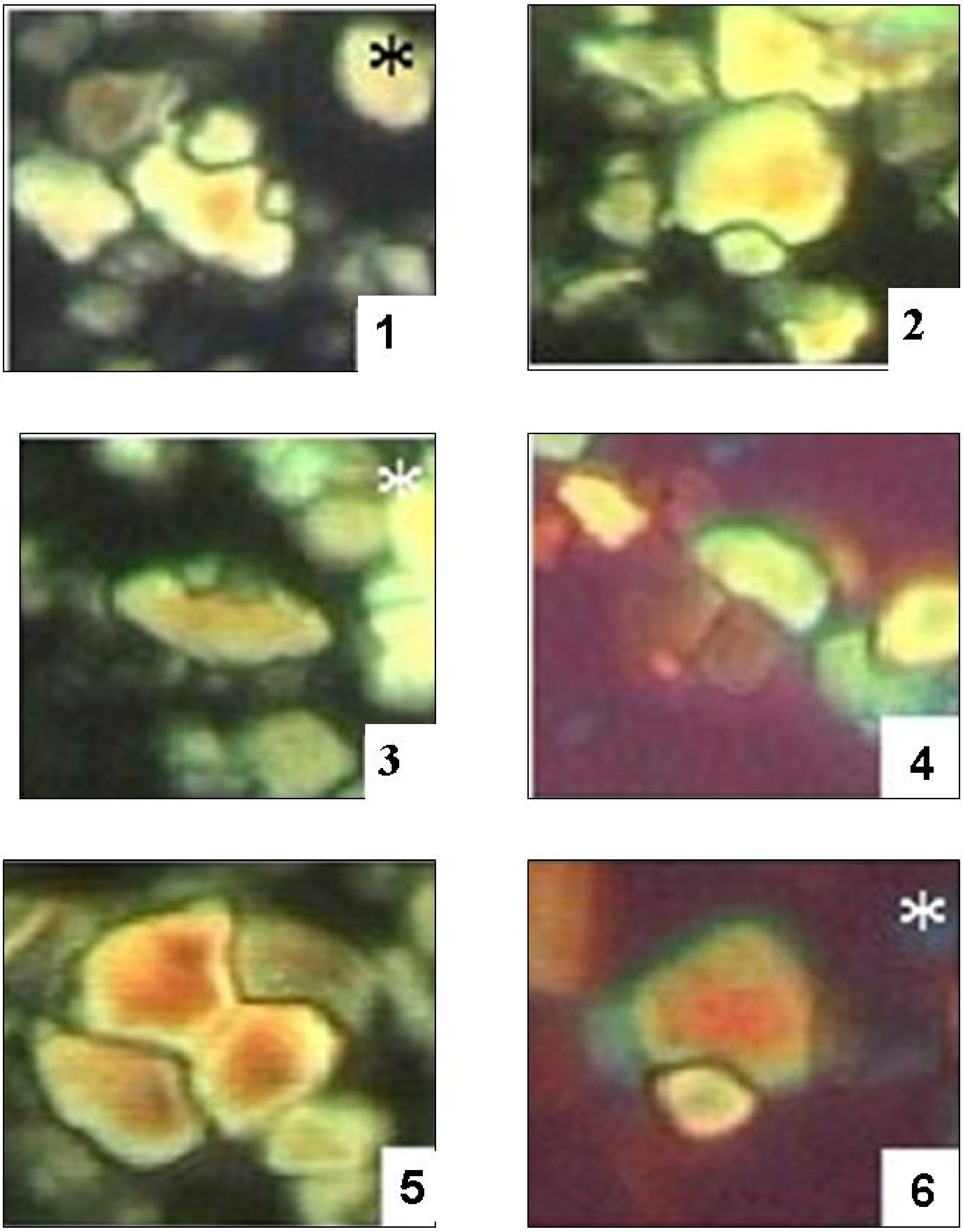
Figure 3. Photomicrograph of *Geminitrabalis scarabaeus*, under cross-polarized light

Figure 4. Photomicrograph of *Disechinatus mediageminus*, under cross-polarized light

Figure 5. Photomicrograph of *Disechinatus bicaudatus*, under cross-polarized light

Figure 6. Photomicrograph of *Geminitrabalis depressus*, under cross-polarized light

PLATE 30



10μm

PLATE 30

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Disechinatus carinatus*, under cross-polarized light

Figure 2. Photomicrograph of *Cephalodidemnum pseudocarenon*, under cross-polarized light

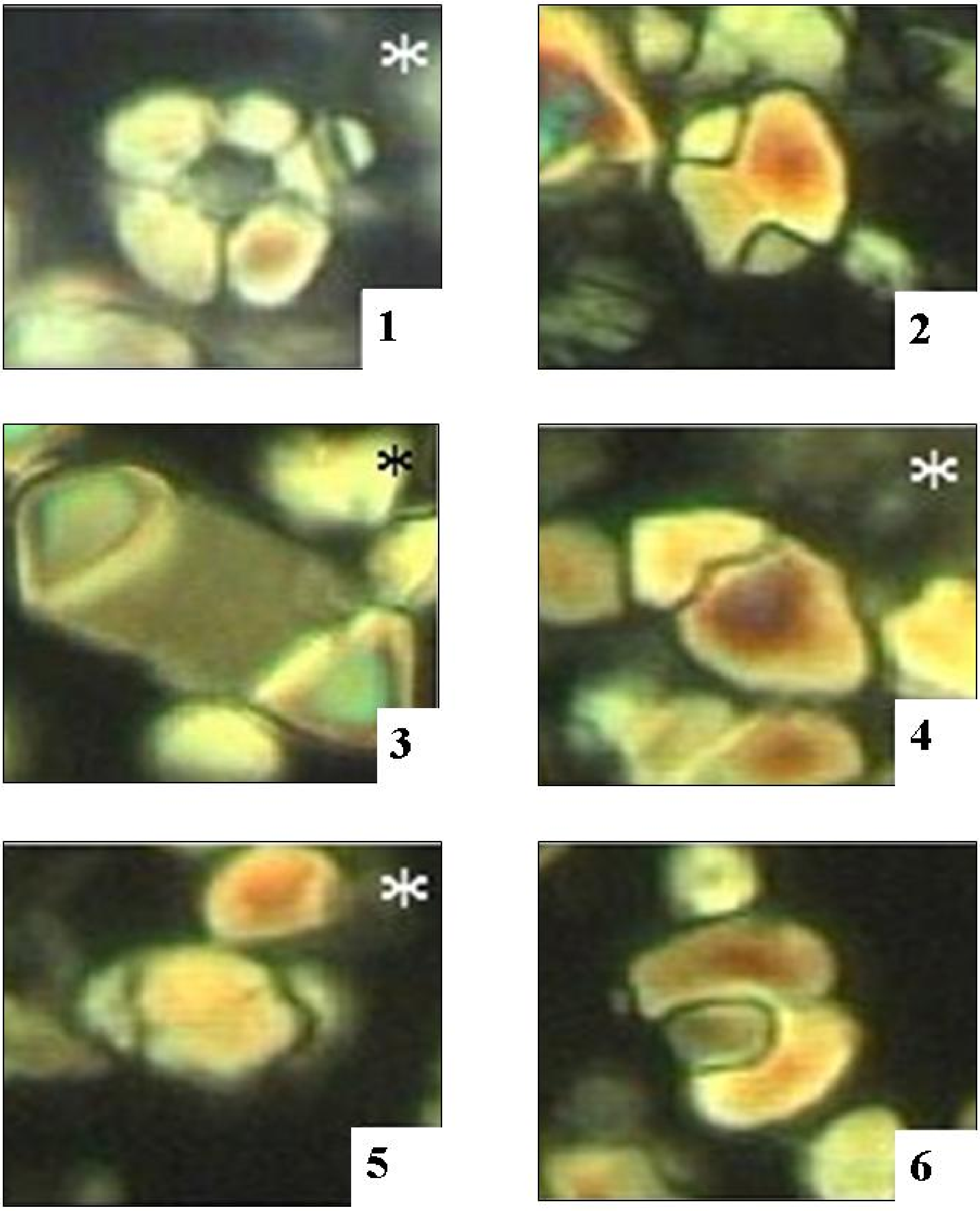
Figure 3. Photomicrograph of *Disechinatus mediageminus*, under cross-polarized light

Figure 4. Photomicrograph of *Disechinatus baculus*, under cross-polarized light

Figure 5. Photomicrograph of *Unabaculus obscurus*, under cross-polarized light

Figure 6. Photomicrograph of *Cephalodidemnum pseudocarenon*, under cross-polarized light

PLATE 31



10μm

PLATE 31

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Hercolithus cricotus*, under cross-polarized light

Figure 2. Photomicrograph of *Unabaculus obscunus*, under cross-polarized light

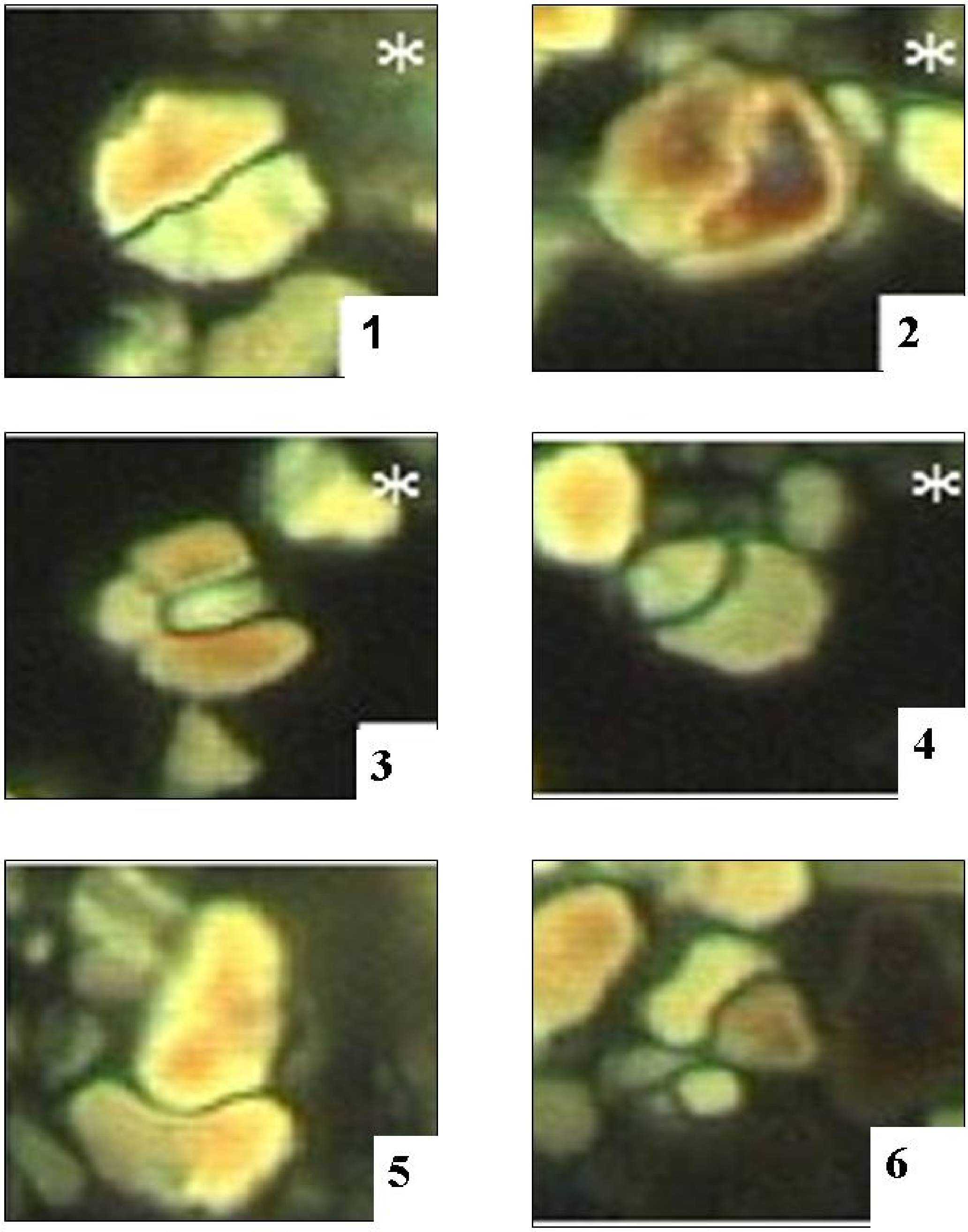
Figure 3. Photomicrograph of *Bactrolithus delicatus*, under cross-polarized light

Figure 4. Photomicrograph of *Cephalodidemnum carenon*, under cross-polarized light

Figure 5. Photomicrograph of *Bicephalodidemnum amphicarenon*, under cross-polarized light

Figure 6. Photomicrograph of *Hercolithus amplexus*, under cross-polarized light

PLATE 32



10μm

PLATE 32

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Didemnobijugatus dichotomus*, under cross-polarized light

Figure 2. Photomicrograph of *Didemnobijugatus zigzag*, under cross-polarized light

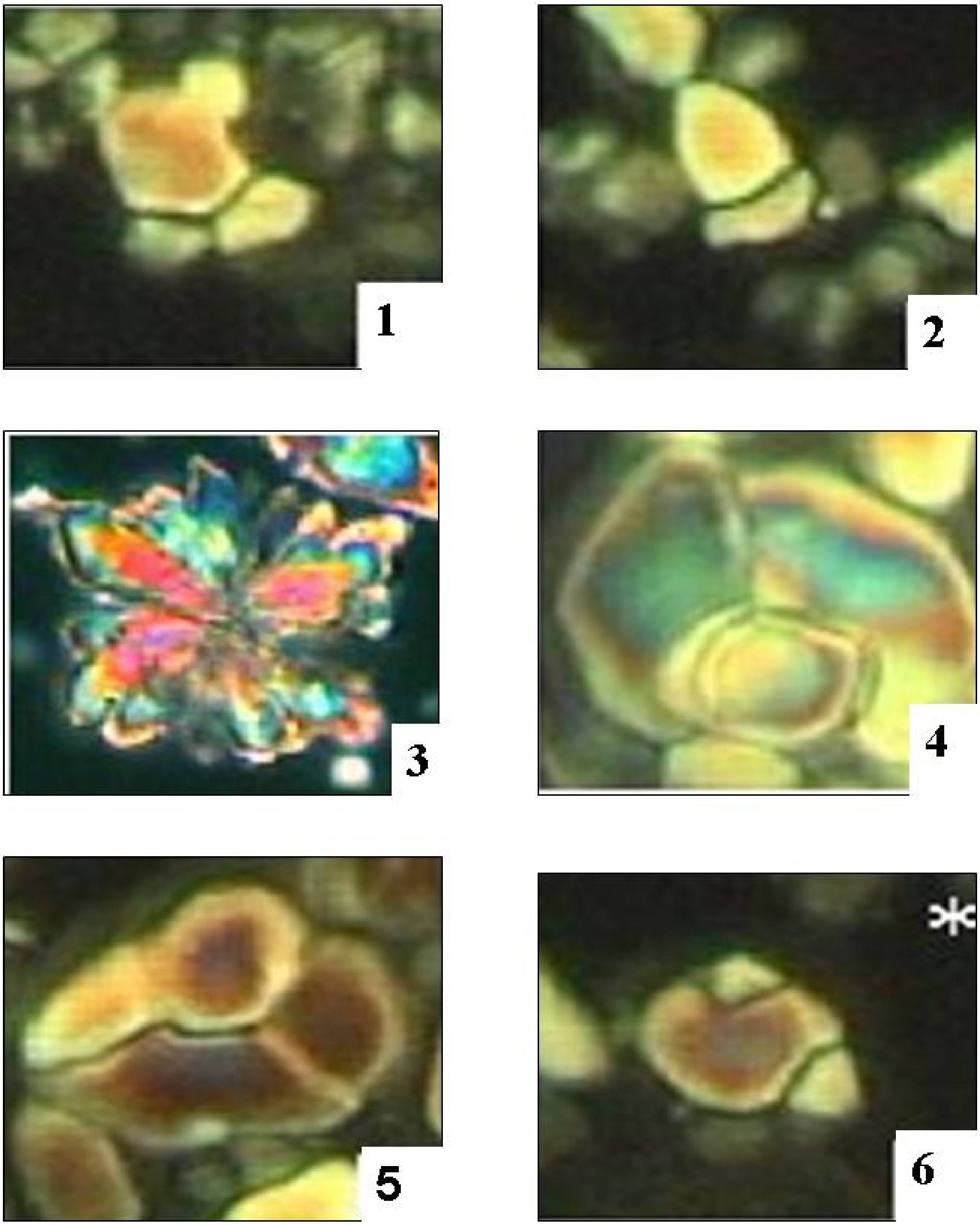
Figure 3. Photomicrograph of *Hercolithus amplexus*, under cross-polarized light

Figure 4. Photomicrograph of *Paleodidiemnum causianus*, under cross-polarized light

Figure 5. Photomicrograph of *Paleodidemnum curvus*, under cross-polarized light

Figure 6. Photomicrograph of *Paleodidemnum coriger*, under cross-polarized light

PLATE 33



10μm

PLATE-33

C PHOTOMICROGRAPH OF ALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Diplintos qatifensis*, under cross-polarized light

Figure 2. Photomicrograph of *Paleodidemnum galbulus*, under cross-polarized light

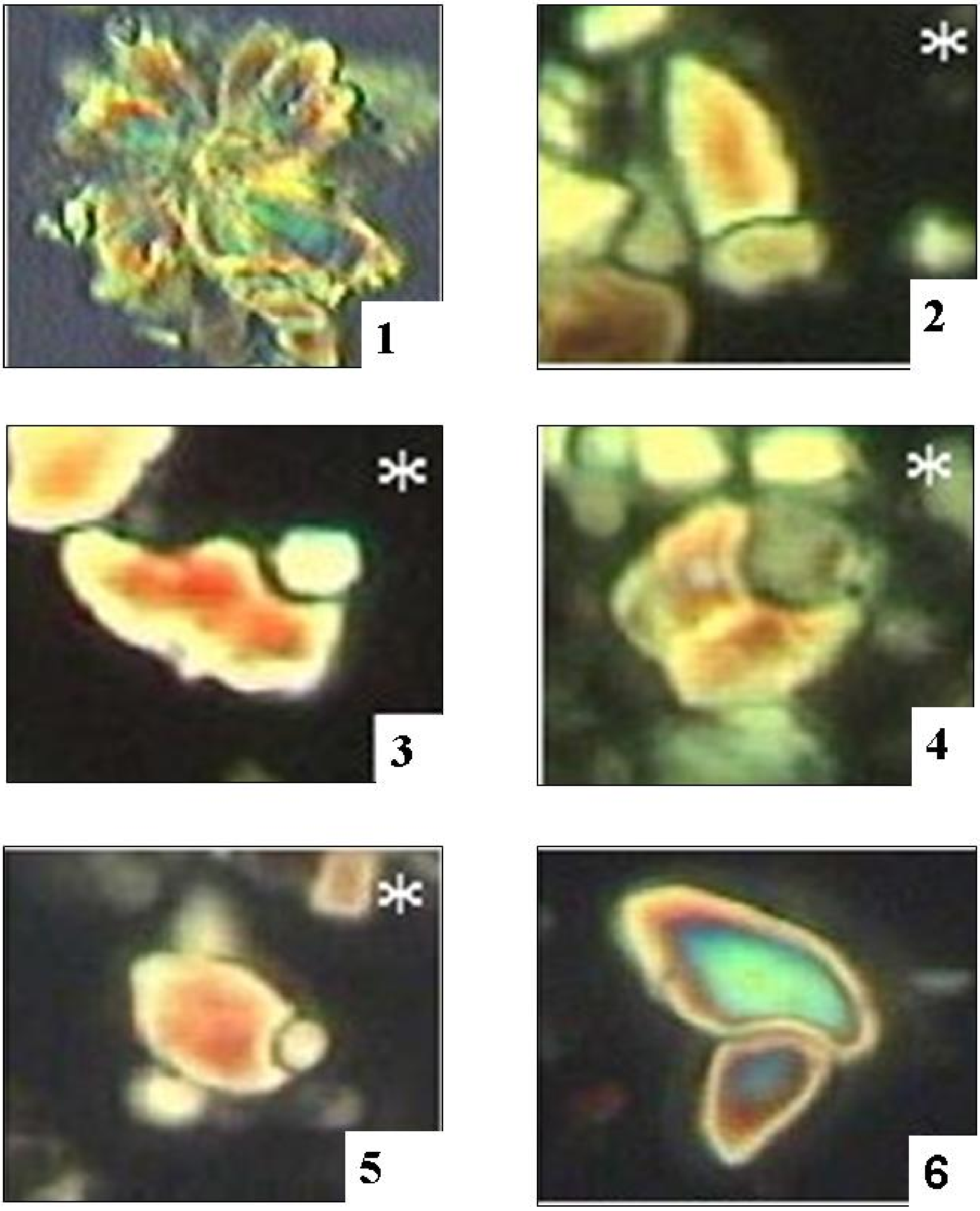
Figure 3. Photomicrograph of *Didemnoides rosetta*, under cross-polarized light

Figure 4. Photomicrograph of *Paleodidemnum caudatus*, under cross-polarized light

Figure 5. Photomicrograph of *Paleodidemnum marjanensis*, under cross-polarized light

Figure 6. Photomicrograph of *Ommalithus arabianica*, under cross-polarized light

PLATE 34



10μm

PLATE 34

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Didemnoides radiatus*, under cross-polarized light

Figure 2. Photomicrograph of *Paleodidemnum procerus*, under cross-polarized light

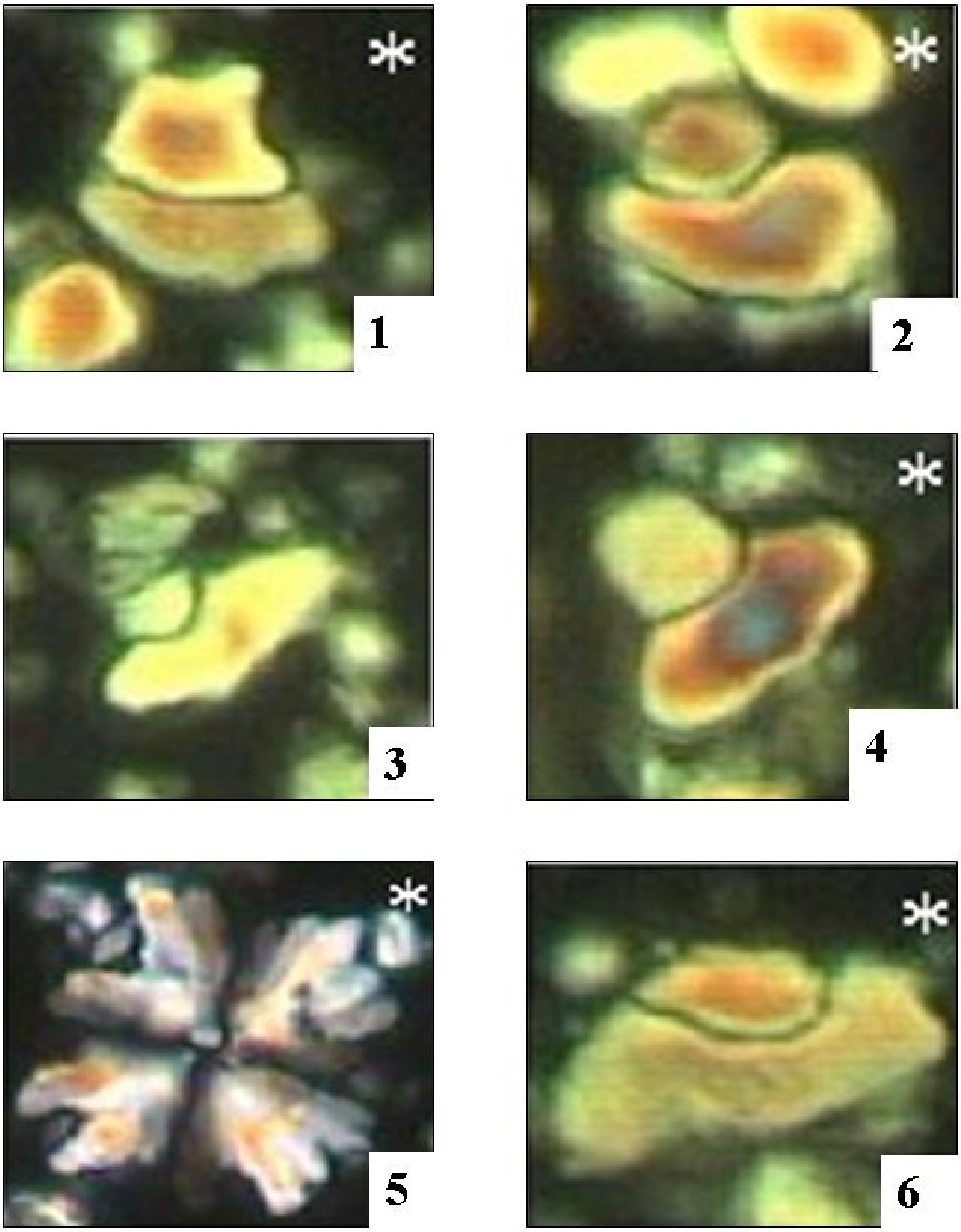
Figure 3. Photomicrograph of *Paleodidemnum pseudoacutus*, under cross-polarized light

Figure 4. Photomicrograph of *Geminitrabalis depressus*, under cross-polarized light

Figure 5. Photomicrograph of *Paleodidemnum caudatus*, under cross-polarized light

Figure 6. Photomicrograph of *P. Caudatus*, under cross-polarized light

PLATE 35



10μm

PLATE 35

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Paleodidemnum Phossonion*, under cross-polarized light

Figure 2. Photomicrograph of *Paleodidemnum acutus*, under cross-polarized light

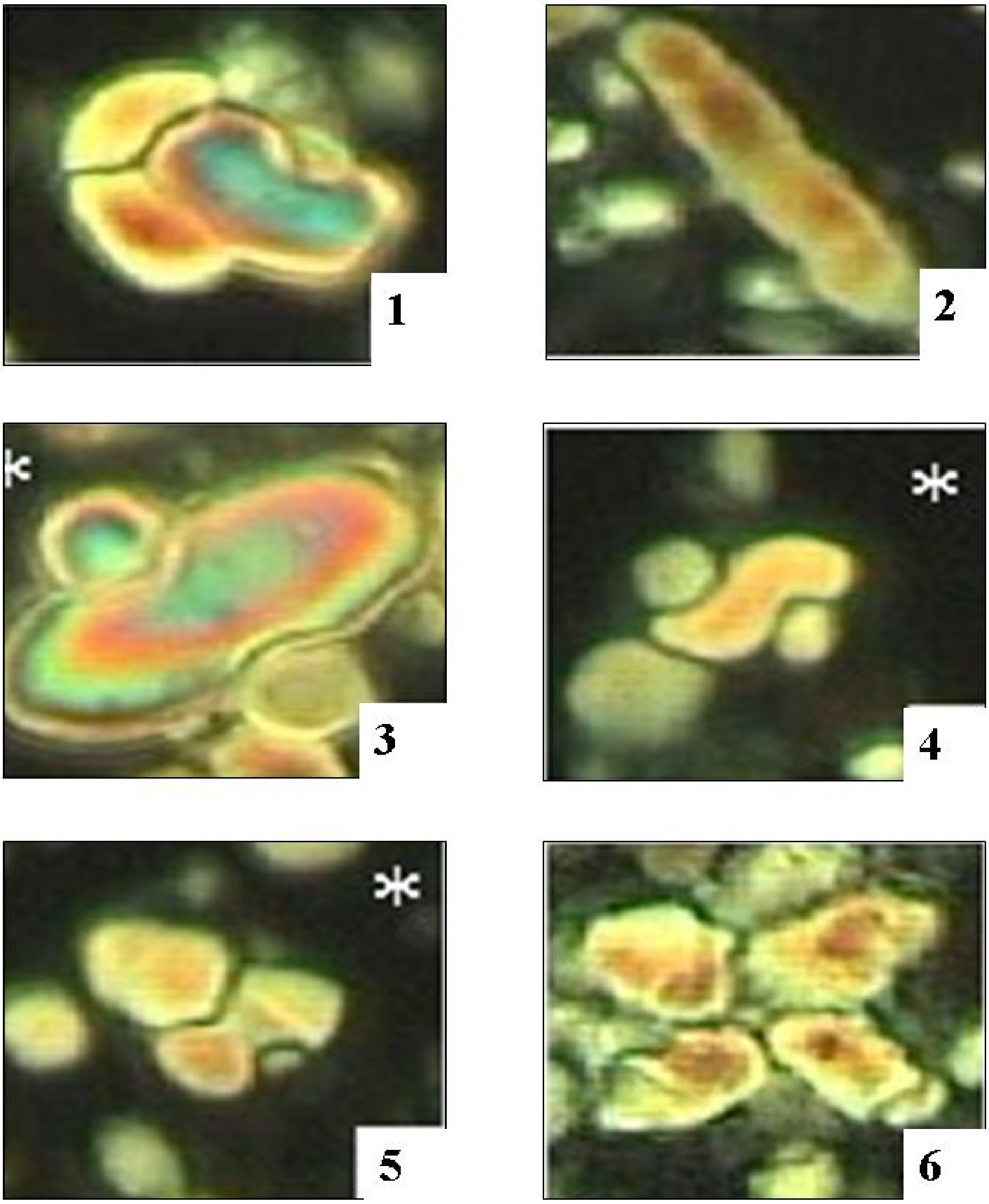
Figure 3. Photomicrograph of *Paleodidemnum metaxy*, under cross-polarized light

Figure 4. Photomicrograph of *Paleodidemnum saudicus*, under cross-polarized light

Figure 5. Photomicrograph of *Cyclagelosphaera omanica*, under cross-polarized light

Figure 6. Photomicrograph of *Paleodidemunm alatus*, under cross-polarized light

PLATE 36



10μm

PLATE 36

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Paleodidemnum saudicus*, under cross-polarized light

Figure 2. Photomicrograph of *Fusellinus elongatus*, under cross-polarized light

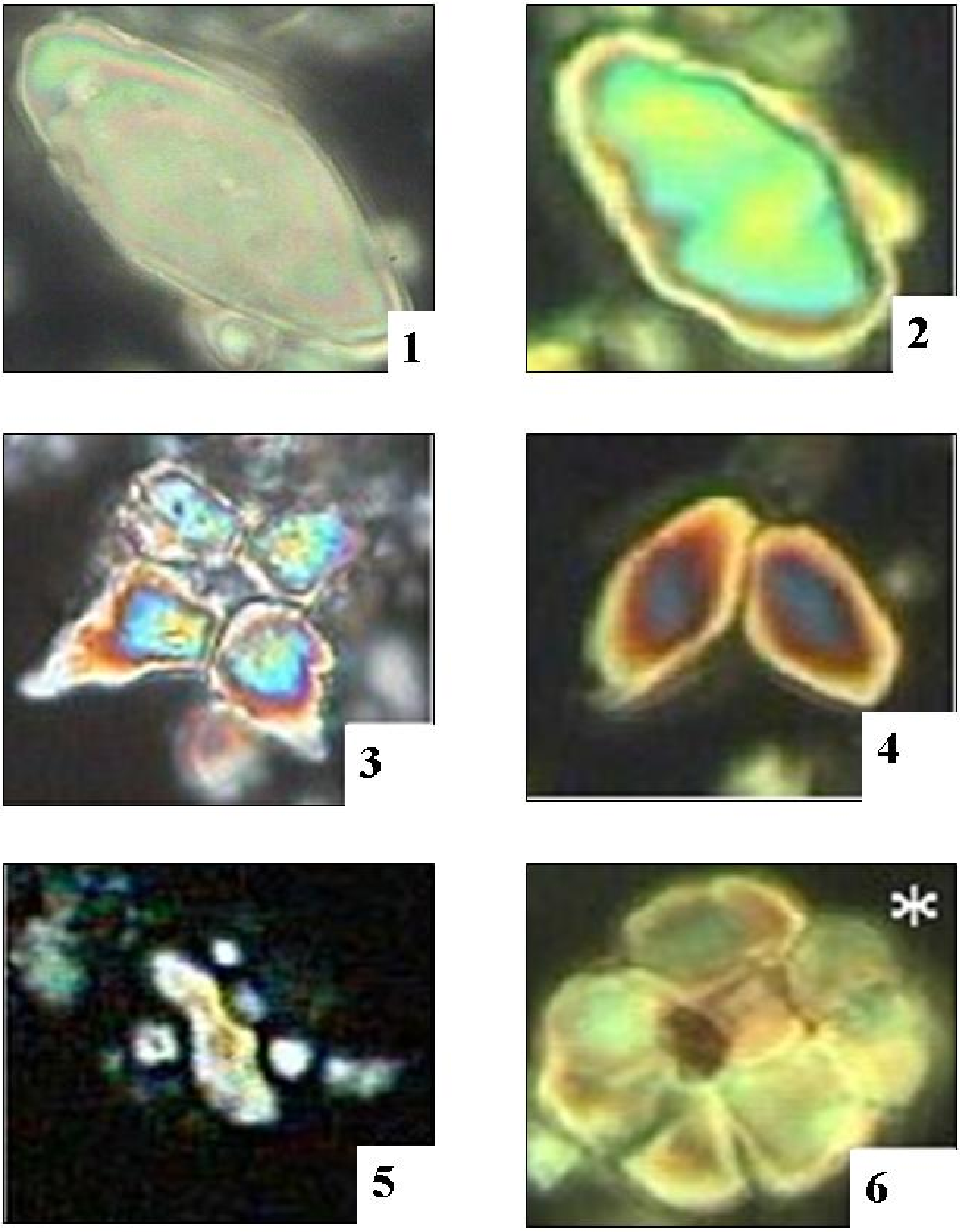
Figure 3. Photomicrograph of *Acinodidemnum lineola*, under cross-polarized light

Figure 4. Photomicrograph of *Acinodidemnum ecpalesis*, under cross-polarized light

Figure 5. Photomicrograph of *Acinodidemnum arcuatus*, under cross-polarized light

Figure 6. Photomicrograph of *Velasquezia minuta*, under cross-polarized light

PLATE 37



10μm

PLATE 37

PHOTOMICROGRAPH OF CALCAREOUS NANNOFOSSILS

Figure 1. Photomicrograph of *Fusellinus gigas*, under cross-polarized light

Figure 2. Photomicrograph of *Fusellinus insolitus*, under cross-polarized light

Figure 3. Photomicrograph of *Velasquezia praegothica*, under cross-polarized light

Figure 4. Photomicrograph of *Fusellinus brevis*, under cross-polarized light

Figure 5. Photomicrograph of *Didemnotribaculus anceps*, under cross-polarized light

Figure 6. Photomicrograph of *Hercolithus petalus*, under cross-polarized light

APPENDIX A

THE JUBAILA FORMATION TYPE AND REFERENCE SECTION IN WADI NISSAH

APPENDIX A.1

THE JUBAILA FORMATION TYPE AND REFERENCE SECTIONS IN WADI NISSAH

Jubaila Limestone sections
Section 1-Wadi Nissah
[Jubaila Limestone reference section composited from three measured increments in Wadi Nissah. the lower part was described by E. L. Berg and R. L. Myers in 1945, the middle by R. A. Bramkamp and S.B. Henry (1948), and the upper by R. W. Powers and H. A. McClure in 1961].

Calcarenite of the Arab Formation (Upper Jurassic).
Jubaila Formation: Thickness (meters)

4. Aphanitic and calcarenitic limestone (6.0m thick):
   Aphanitic limestone, tan to yellow, tight, chippy-weathering, partially rec-rystallized; single thin bed of gray, tight, skeletal calcarenitic limestone n-ear middle--1.5
   Calcarenitic limestone, tan to yellow, tight, chippy-weathering, skeletal; occasional thin layers of aphanitic limestone and bed of gray-brown, tigh-tly cemented calcarenite near middle and at base-----------------------------------4.5
3. calcarenite (7.0m thick):
   Pellet-skeletal-calcarenite, gray to golden-brown, tighly cemented; fine to medium- grained, rarely sandy; thin bed of golden-brown, tightly cemented, partially dolomitized, coarse stromatoporoid carbonate near base. Part of interval is poorly exposed--7.0
2. Calcarenitic limestone and calcarenite (20.5 m thick):
   Dolomite, dark-reddish-brown, compact, finely crystalline-----------------------1.0
   Limestone and calcarenite; complexly interbedded, off-white to reddish-brown, partially dolomitized, tight, fine-to medium-grained, pellet-skeletal calcarentic, limestone and cream-colored to golden-brown, tightly cement-ed, partially recrystallized, fine- to medium-grained, pellet-skeletal calca-renite---12.5
   Calcarenitic limestone, cream to yellow, tight, partially dolomitized, fine-to medium grained, pellet-skel rare thin beds of aphanitic limestone, co-mmon scattered coarse- grained shell debris at various levels.--------------------7.0
1-Aphanitic limestone (84.8m thick):
   Aphanitic and calcarenitic limestone, approximately equal amounts of co-mplexly interbedded, cream-colored to yellow, tight commonly partially

dolomitized, very rarely sandy aphanitic limestone and golden-brown, tight, fine to medium grained partially dolomitized, pellet-skeleltalcacarenitic limestone; occasional thin beds of tan, tightly cemented calcarenite and finely crystalline dolomite---22.0
aphanitic limestone, cream-colored to tan, chippy to rubbly-weathering tight, rarely chalky, commonly sandy; occasional thin beds of brown, pellet-skeletal calcarenite limestone and tightly cemented calcarenite---------------62.8

Total thickness of Jubaila limestone---118.3

APPENDIX B

VERTICAL DISTRIBUTION OF SELECTED FORMS OF BIOCOMPONENTS WITHIN STUDIED LOCALITIES.

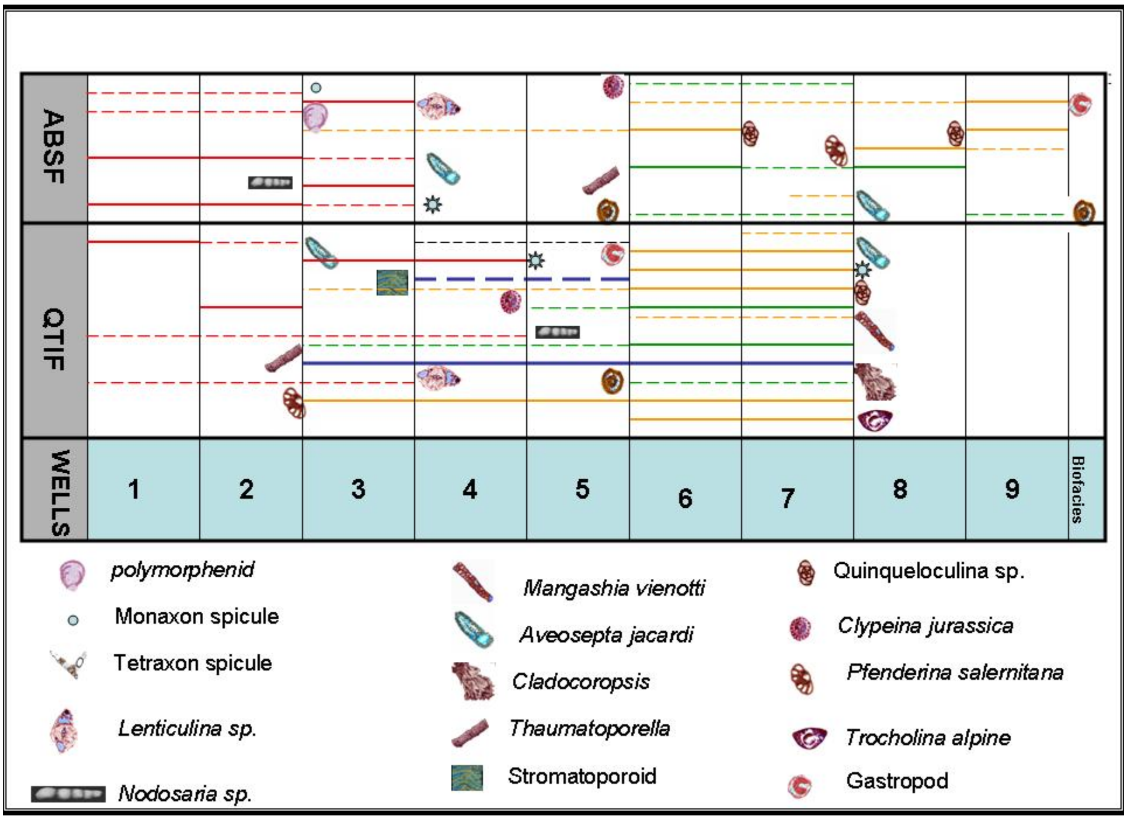


Figure B.1. Micropalaeontological variation of selected forms and biofacies of ABSF and QTIF wells.

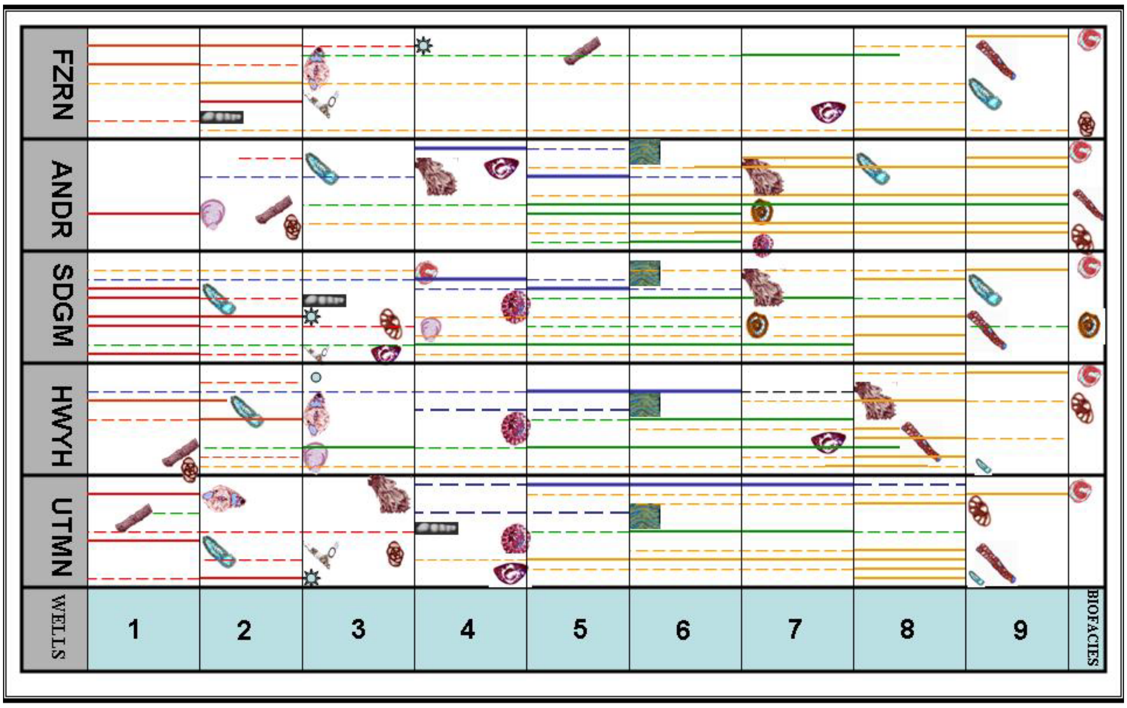


Figure B.2.Micropalaeontological variation of selected forms and biofacies of Ghawar wells.

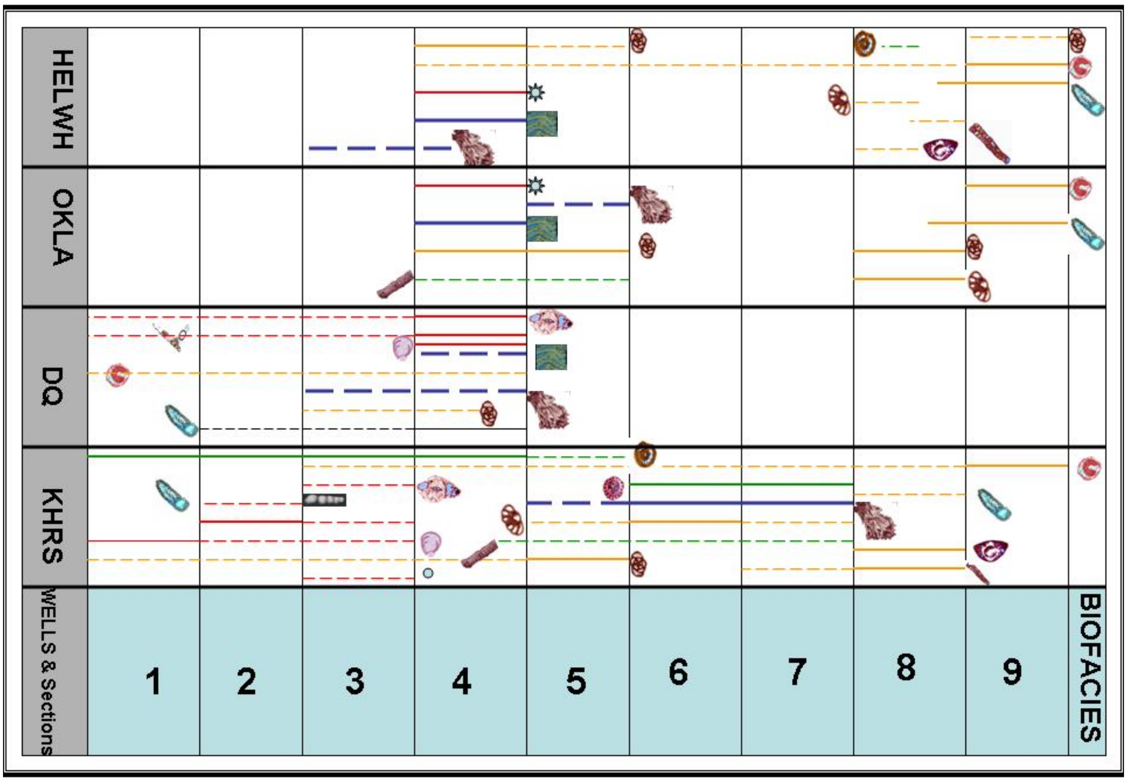


Figure B.3. Micropalaeontological variation of selected forms and biofacies of outcrops sections and KHRS well.

APPENDIX C

HAND DRAWN CARTOON SHOWING THE LAST STROMATOPOROID FRAGMENTS AT JUBAILA FORMATION TOP.

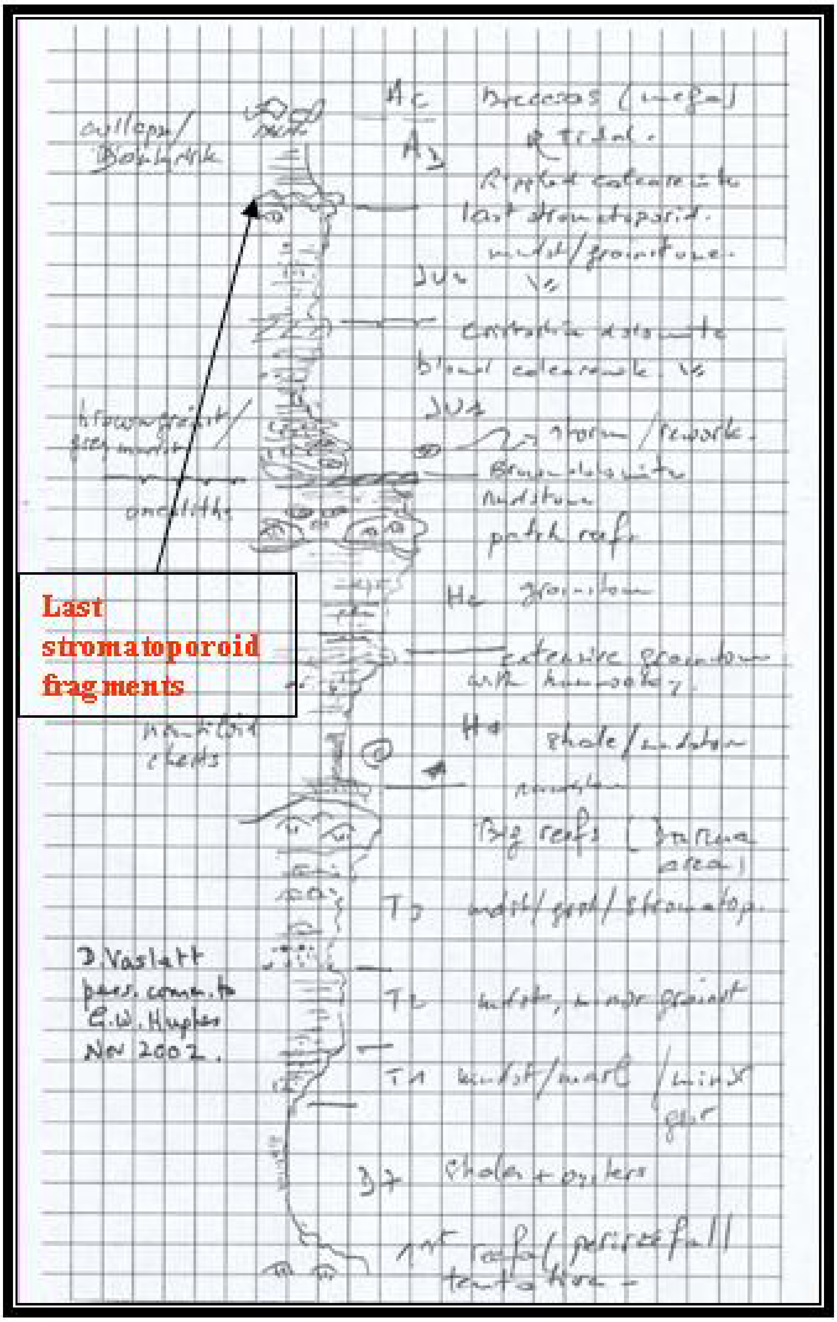


Figure C.1. Dr. Vaslet (personal communication with Dr. G.W. Hughes Nov. 2002) hand drawn cartoon to show that the last stromatoporoid fragment is at the top of the Jubaila Formation.

Vita

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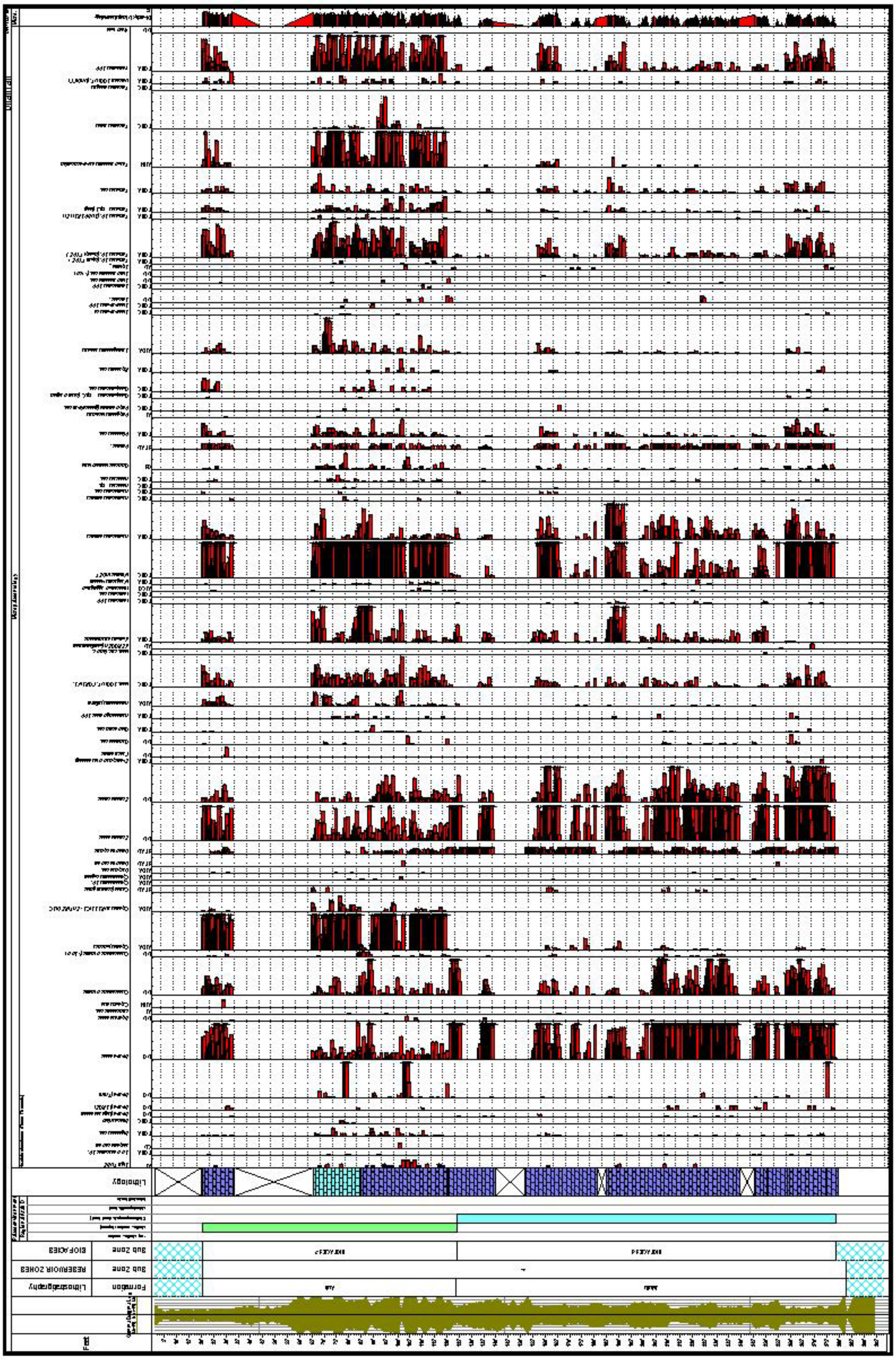
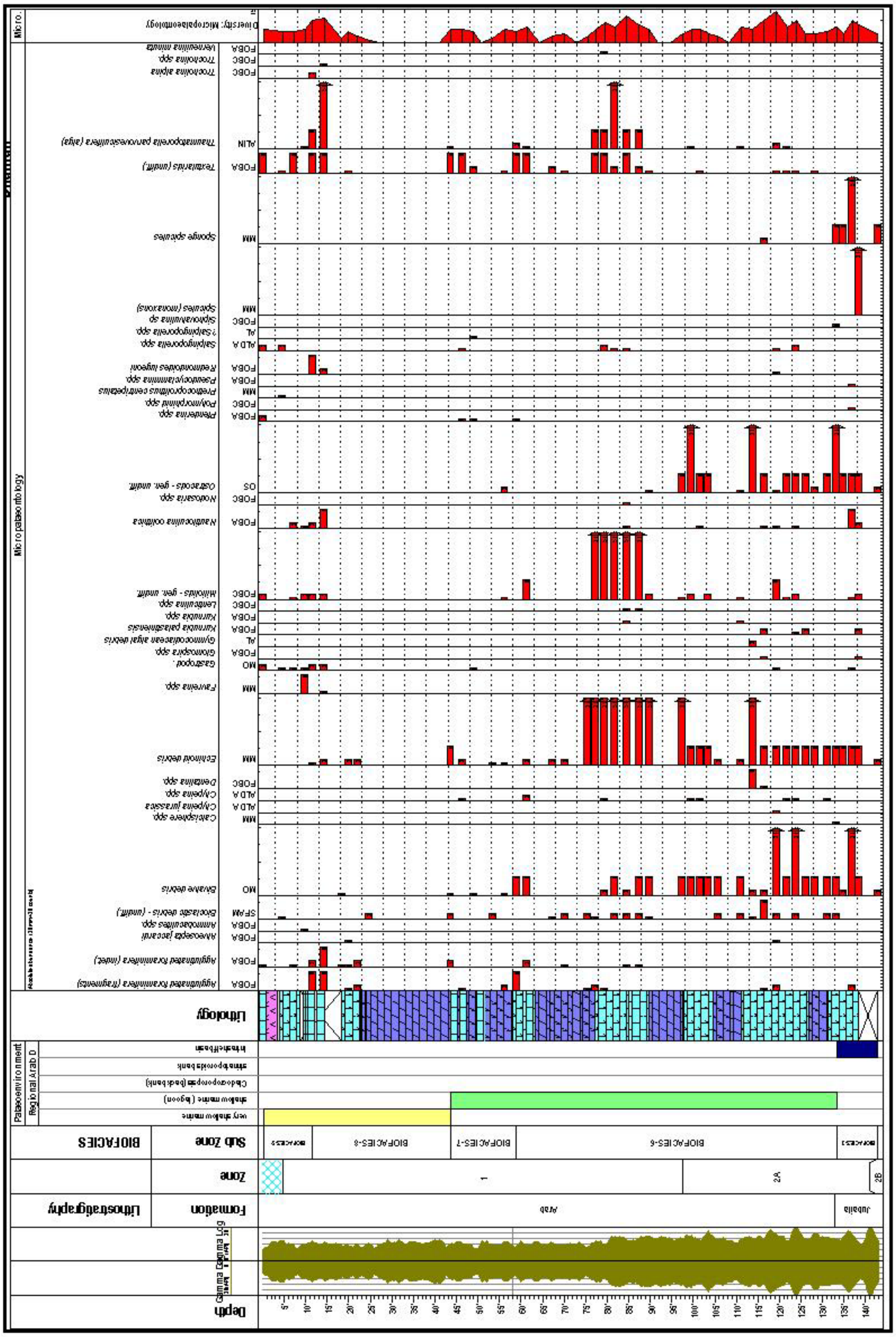
- Joined Earth Sciences Department, King Fahd University of Petroleum and Minerals as a part time student in February, 2002.
- Received Master of Science (Msc.) degree in Geology from Earth Sciences Department KFUPM, in June 2005.

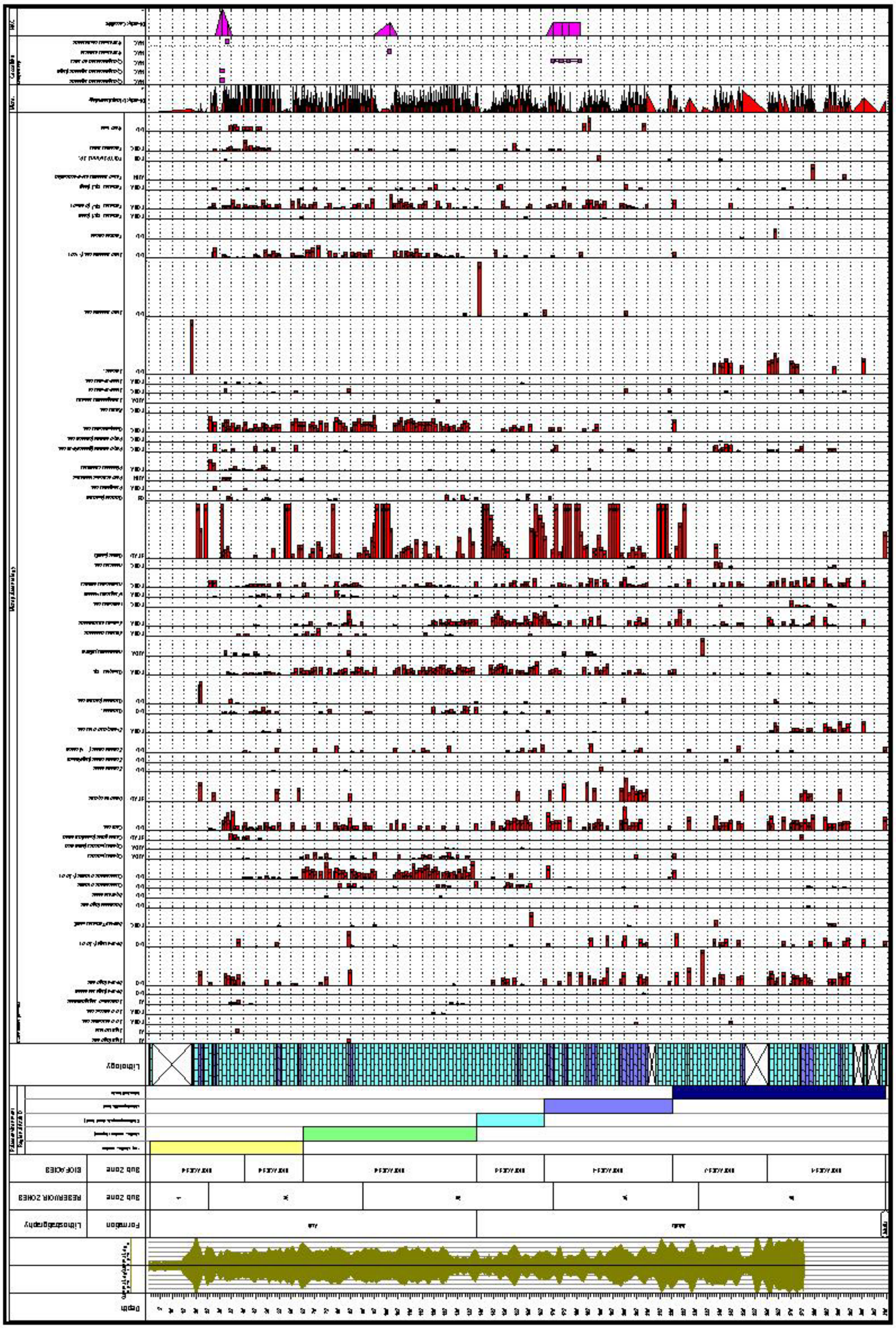
ENCLOSURES



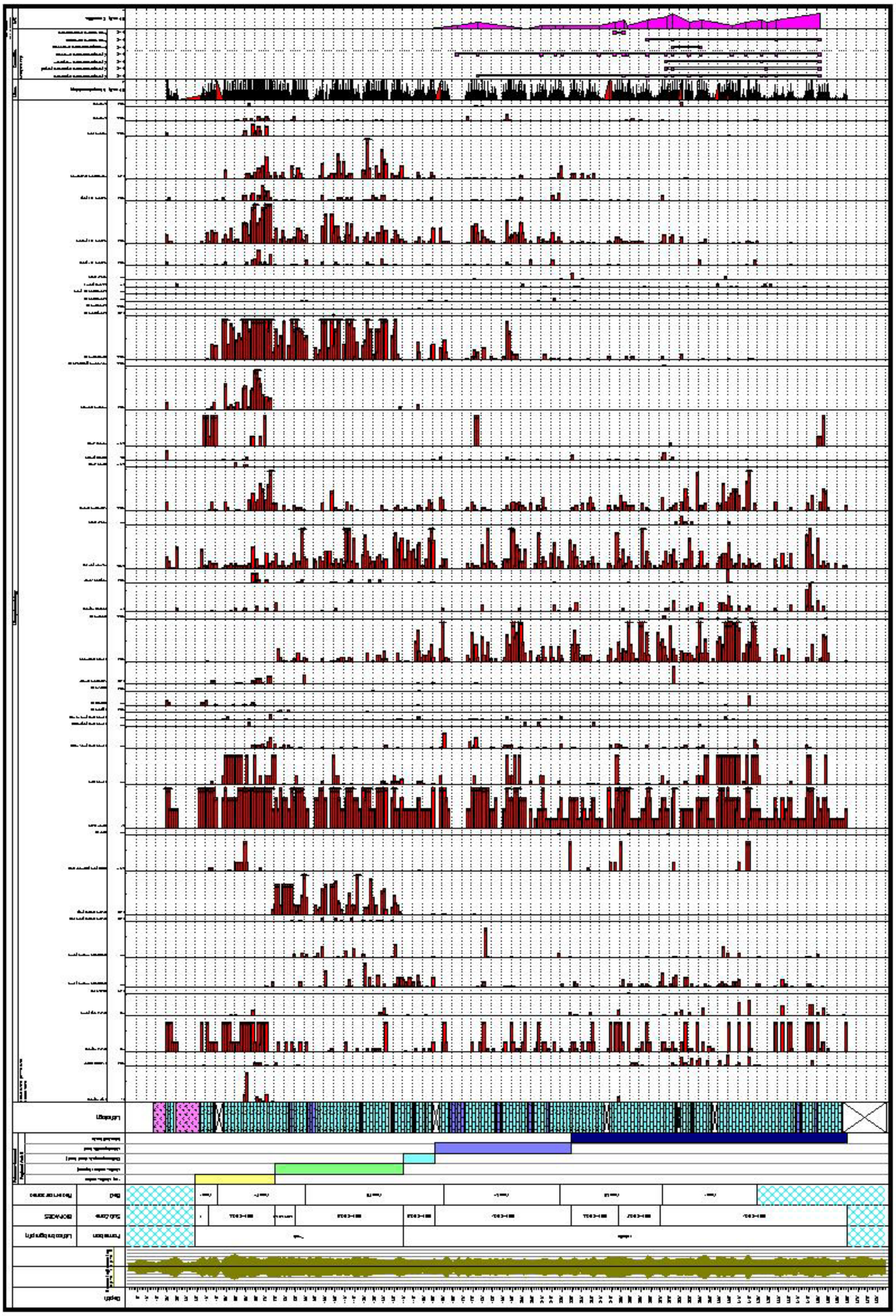
ENCLOSURE 1. ABSF WELL



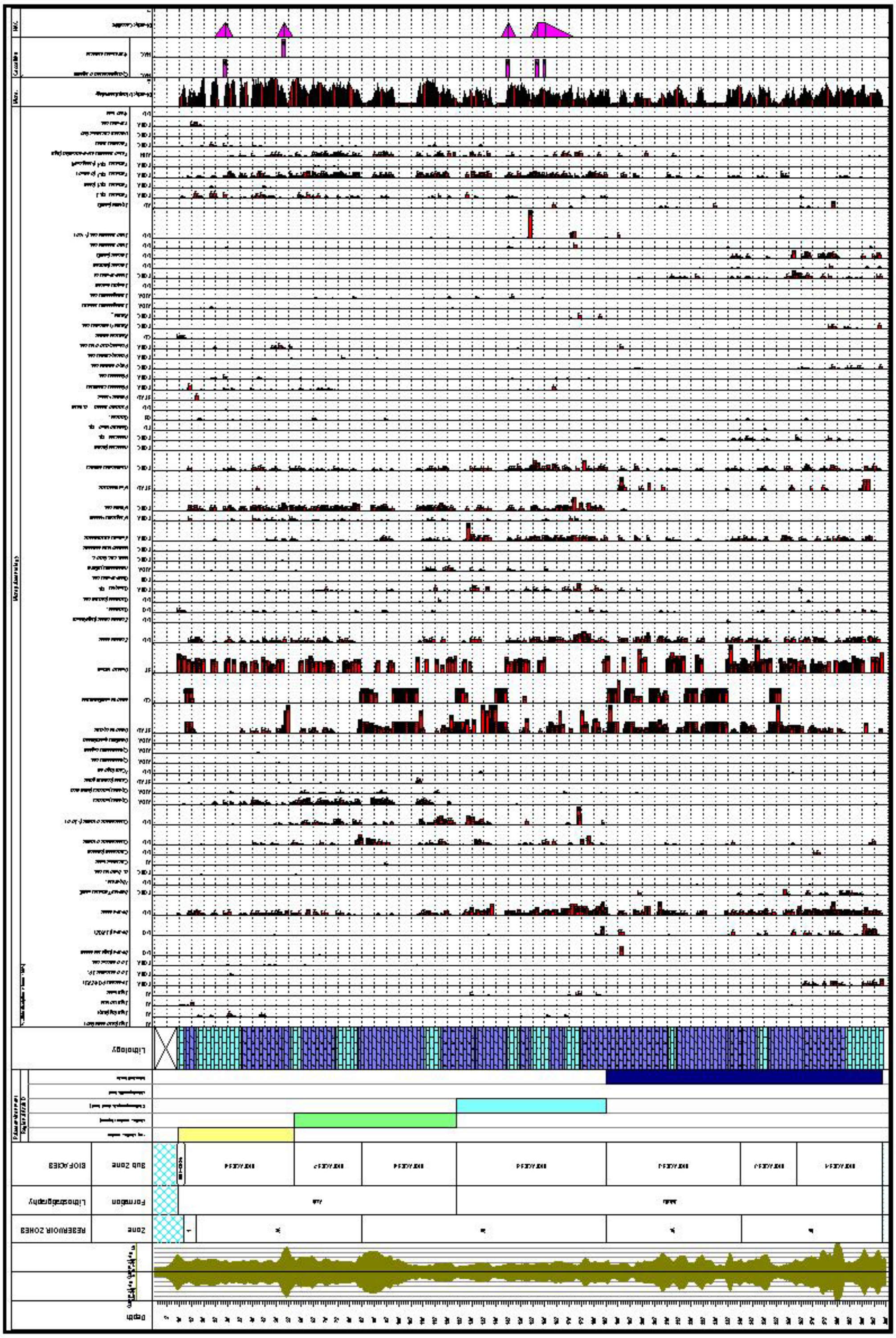
ENCLOSURE 2. QTIF WELL



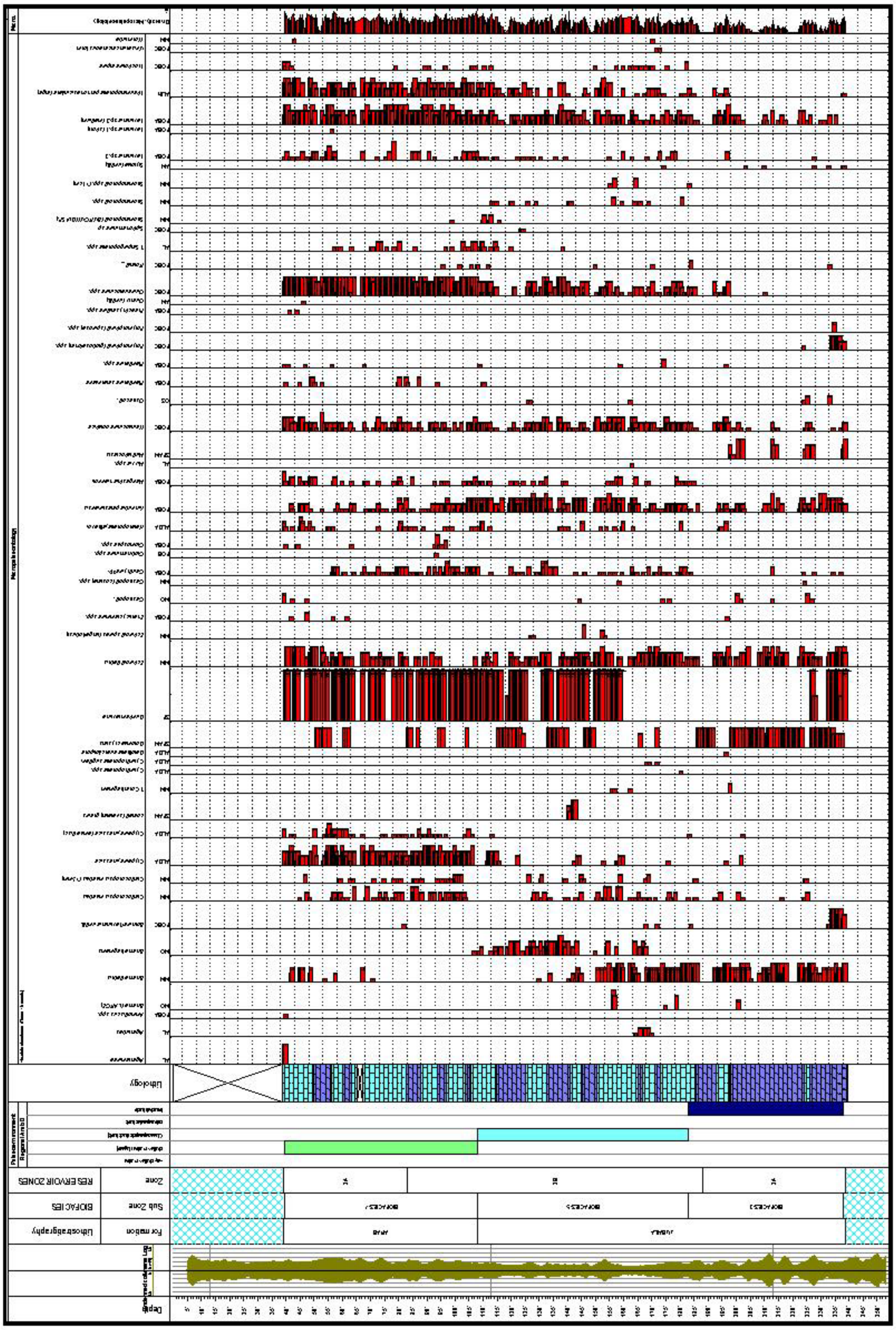
ENCLOSURE 3. UTMN WELL



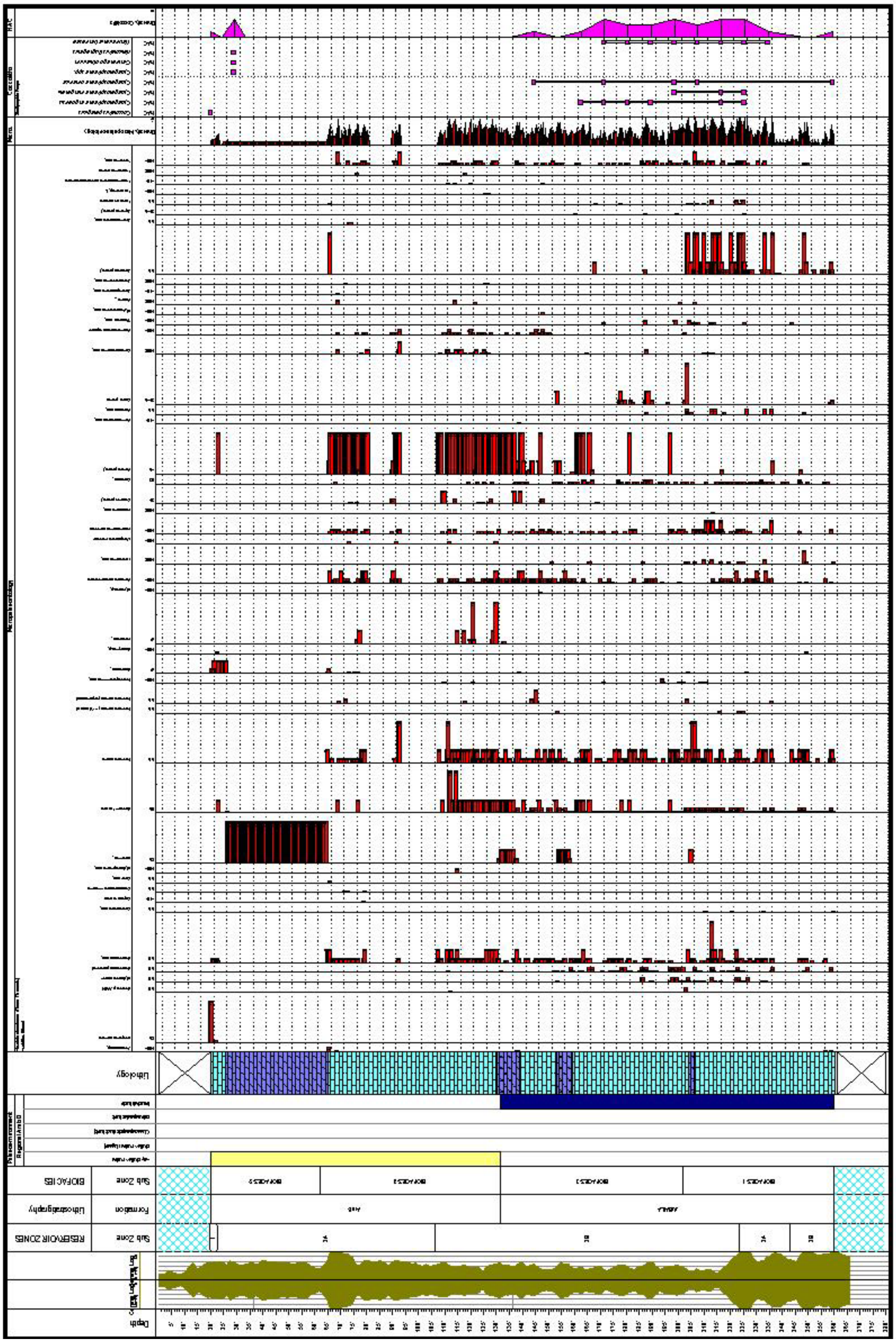
ENCLOSURE 4. HWYH WELL



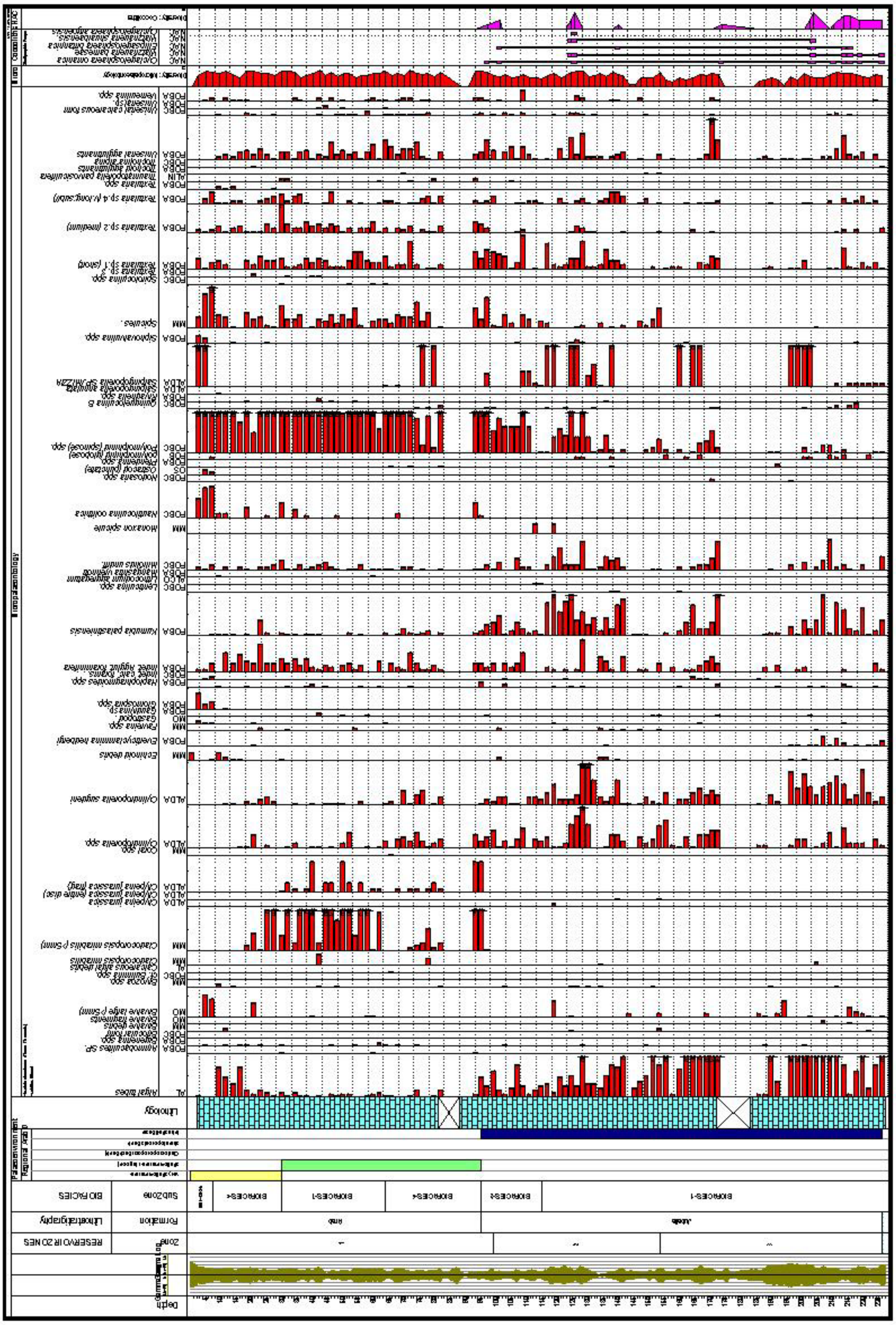
ENCLOSURE 5. SDGM WELL



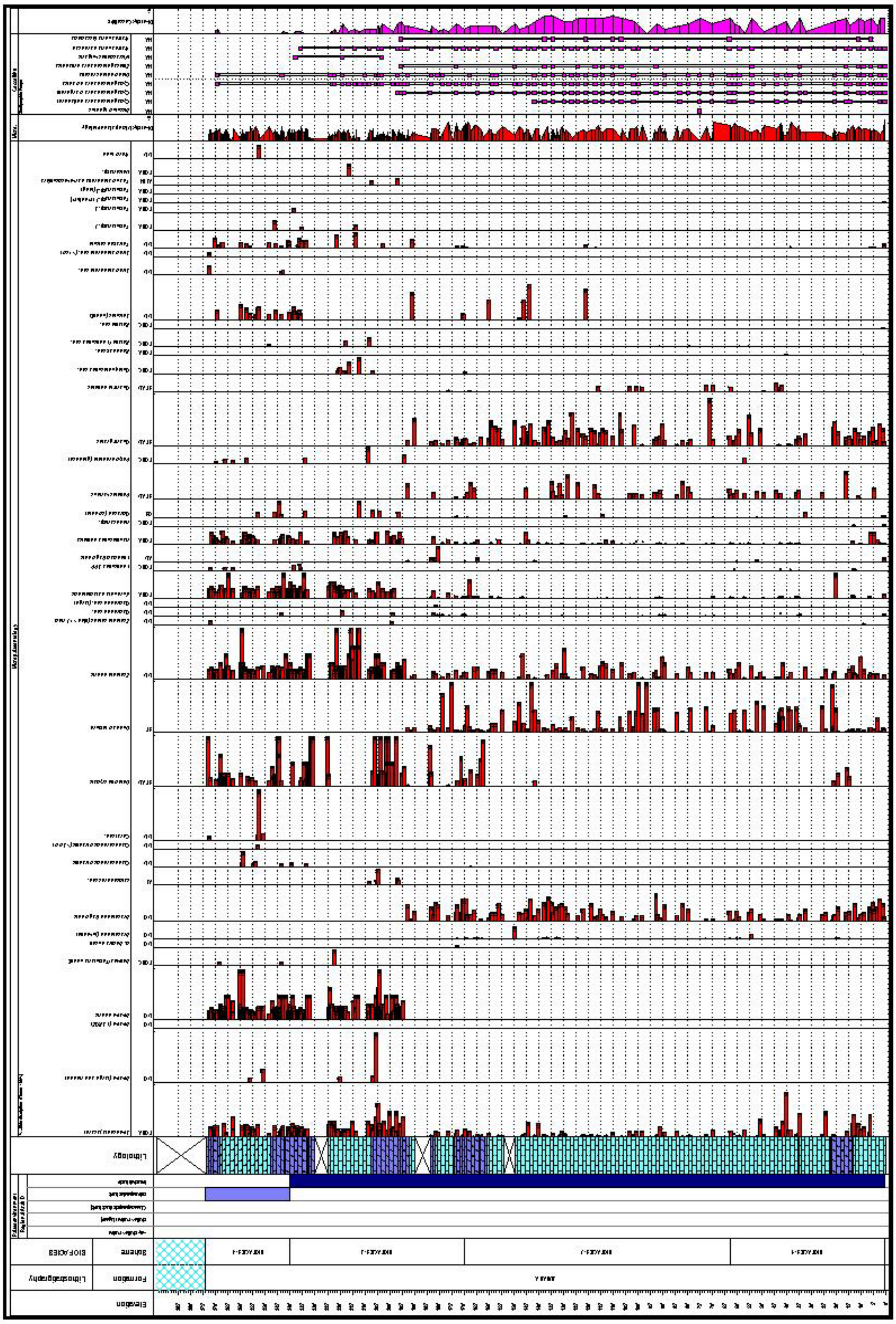
ENCLOSURE 6. ANDR WELL



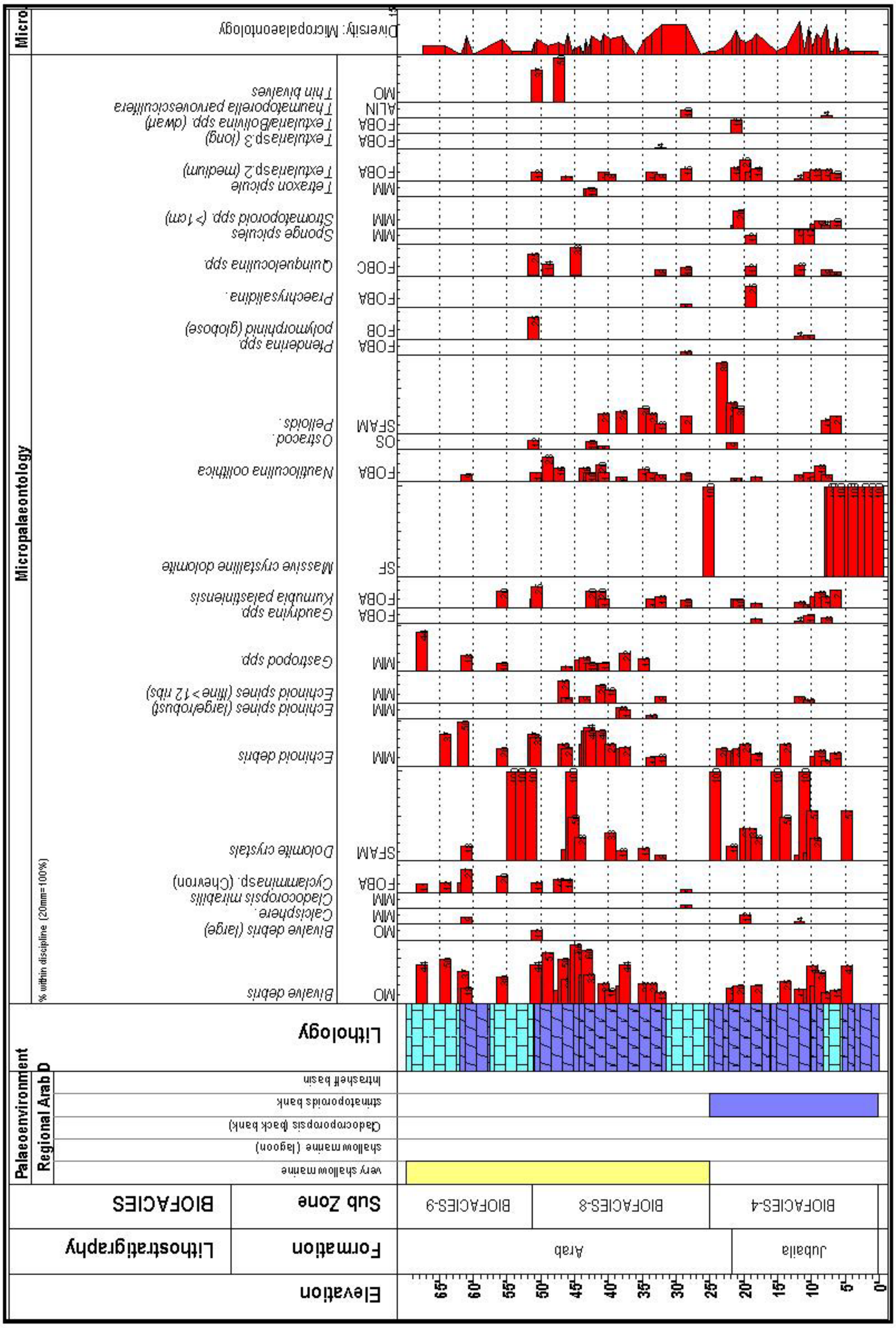
ENCLOSURE 7. FZRN WELL



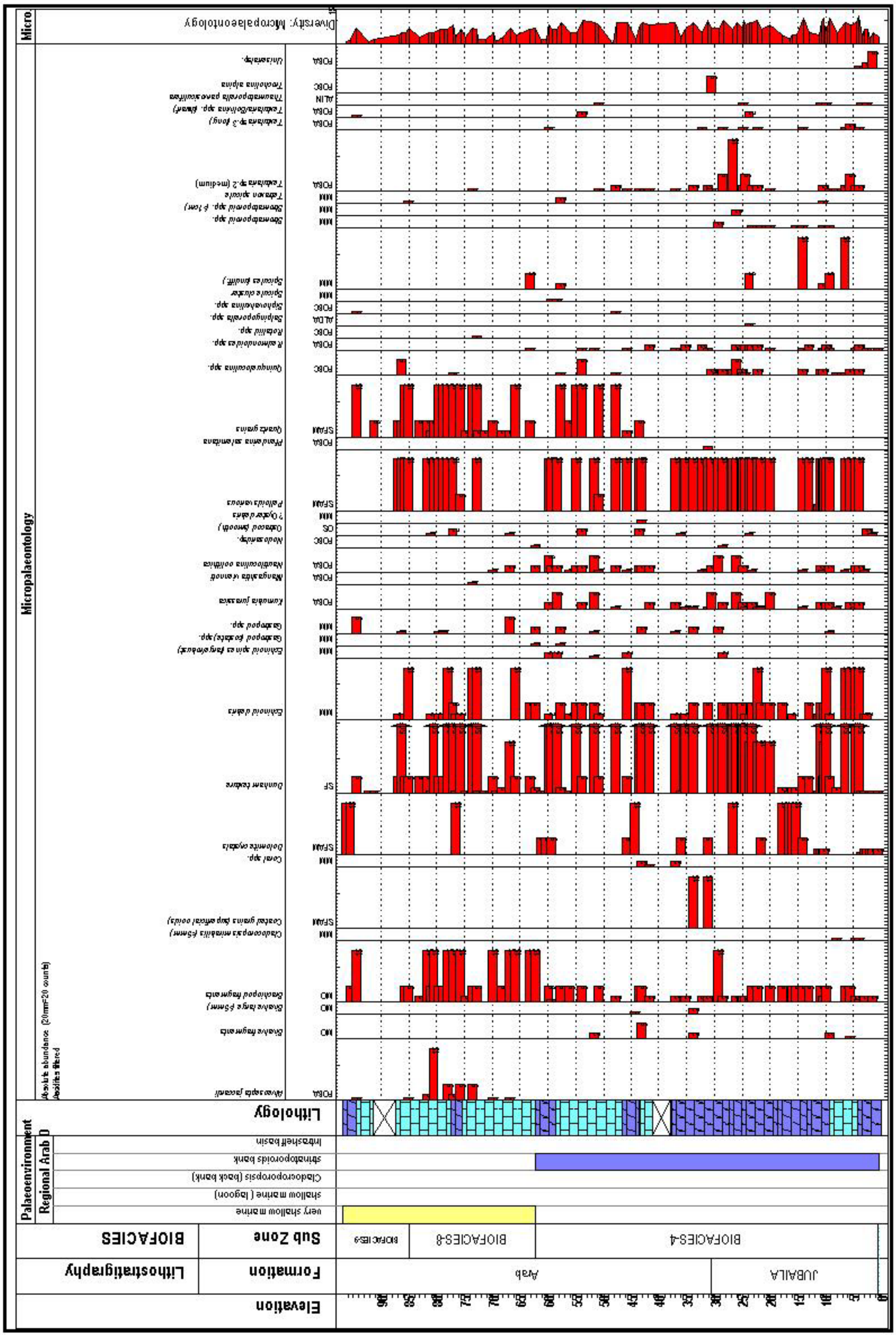
ENCLOSURE 8. KHRS WELL



ENCLOSURE 9. DQ SECTION



ENCLOSURE 10. OKLA SECTION



ENCLOSURE 11. HELAWH SECTION